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CANADIAN JOURNAL OF SOIL SCIENCE

The Agricultural Institute of Canada publishes the "*Canadian Journal of Soil Science*" and two other scientific journals devoted to the publication, in English and French, of the results of original scientific research. Matters of general policy concerning these journals are the responsibility of an Editorial Policy Board, consisting of representatives of specified scientific societies, the Canada Department of Agriculture, and the Agricultural Institute of Canada. Science Editors for each Journal are responsible for assisting the Editorial Policy Board in reviewing manuscripts.

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CANADIAN JOURNAL OF SOIL SCIENCE

VOLUME 41

AUGUST, 1961

No. 2

ASPECTS OF THE SULPHUR STATUS OF THREE QUEBEC SOILS¹

L. E. LOWE² AND W. A. DeLONG³
Macdonald College, Quebec

[Received for publication June 23, 1960]

ABSTRACT

Total sulphur, easily soluble sulphur, and the amounts of sulphur extracted by strongly acidic and strongly alkaline solutions were determined on samples from three Quebec soils, two podzols and one brown forest soil.

Total sulphur was determined, following oxidation in the Parr oxygen bomb, by the colorimetric methylene blue method. The results obtained by this procedure were markedly higher than those obtained by the gravimetric method following bomb oxidation or oxidative fusion with sodium peroxide and sodium carbonate.

Evidence was obtained suggestive of the existence of sulphate-sulphur in association with the organic fraction of these soils.

INTRODUCTION

In 1945 Evans and Rost (4) pointed out that sulphur was an element unjustifiably neglected by soil workers. The situation has changed little in 15 years. This neglect may be attributed in part to the fact that studies undertaken in the earlier part of the century indicated that soil and atmospheric sources were in most cases able to supply crop needs for this element, and in part to the lack of convenient methods for determining the element (10, 19).

In view of the increasing use of concentrated fertilizers, lacking significant amounts of sulphur as incidental impurities, and of the numerous cases of sulphur deficiency being reported (7, 11, 12, 16, 18), it is becoming still more important to extend our knowledge of the chemical nature and behaviour of soil sulphur.

Most of the work undertaken in the past has been directed towards studies of the distribution of sulphur in such fractions as humus sulphur, total organic sulphur or easily soluble sulphate, especially the latter. The main conclusions from these studies have been that, in temperate regions, the organic sulphur is the main reservoir of the element in the soil, and that the easily soluble sulphate fraction is very variable but in general small in amount (4, 14).

The aims of the present investigation were to assess the total sulphur status of some Quebec soils, to gain information on the extractability of the sulphur by various solvents and on the chemical form of sulphur in the extracts.

¹Contribution from the Faculty of Agriculture, McGill University, Macdonald College, Que. Macdonald College Journal Series No. 455. Financial support from the Quebec Department of Agriculture, and the Canada Experimental Farms Service is gratefully acknowledged.

²Research Assistant in Chemistry, Macdonald College.

³Professor of Chemistry, Macdonald College.

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Most of the work undertaken in the past has been directed towards studies of the distribution of sulphur in such fractions as humus sulphur, total organic sulphur or easily soluble sulphate, especially the latter. The main conclusions from these studies have been that, in temperate regions, the organic sulphur is the main reservoir of the element in the soil, and that the easily soluble sulphate fraction is very variable but in general small in amount (4, 14).

The aims of the present investigation were to assess the total sulphur status of some Quebec soils, to gain information on the extractability of the sulphur by various solvents and on the chemical form of sulphur in the extracts.

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MATERIALS AND METHODS

Samples of three Quebec soils were used in this study. Two were podzols, belonging to the Sherbrooke and Greensboro series (3) and the other a brown forest soil of the Grenville series (8). All three sites had been under permanent pasture and, as far as was known, had never received applications of inorganic fertilizers.

Total sulphur was determined by a new procedure, involving the oxidation of an intimate mixture of sample and benzoic acid (both ground to pass 60-mesh sieve) in the Parr oxygen bomb (17), under 15 atmospheres pressure of oxygen. Pellets ignited in the bomb contained 0.6-1.0 grams of soil. The sulphate formed was estimated by the colorimetric method of Johnson and Nishita (6). The latter is referred to in this paper as the methylene blue method. When total sulphate was determined by fusion and gravimetric methods, the procedures employed were those described by the A.O.A.C. (1).

Unless otherwise stated, determinations of easily soluble sulphur, humus sulphur and organic sulphur fractions were made by direct application of the methylene blue method to the fraction concerned.

Sulphate in extracts made with concentrated HCl was determined by the method of Bertolacini and Barney (2) modified for use with the Evelyn colorimeter, which has a 1-inch light path. The absorbence was read at 540 $m\mu$ instead of at 332 $m\mu$ as recommended by the authors of the method.

Prior to the sulphate determination, organic materials were removed from the extract by shaking for 20 minutes with activated charcoal (Norite), and filtering. The charcoal was previously washed with NaOH and HCl to remove any contaminants.

Extractions for easily soluble sulphur were made by shaking the samples with 0.001 N HCl for 2 hours at a ratio of 1:10. This method had previously been used by Little (9) among others, except that he used a ratio of 1:2.5. Extractions of this fraction with other reagents (Table 4) were carried out under the same conditions unless otherwise stated. In the study of the temperature effect, a ratio of 1:5 was used and a time of contact of 100 minutes without shaking.

Extractions for humus sulphur were made with 4 per cent ammonium hydroxide according to the procedure of Evans and Rost (4). The success of MacLean (13) in extracting organic phosphorus compounds with 0.5 M sodium bicarbonate raised to pH 10 by addition of sodium hydroxide, for

TABLE 1.—TOTAL SULPHUR BY THREE METHODS

Method	Number of determinations	Mean value in p.p.m. S	
		Greensboro	Grenville
Fusion and gravimetric	2	—	487
Bomb and gravimetric	2	260	860
Bomb and colorimetric	6	440	1385

16 hours at 90°C., led to the use of this procedure for the extraction of organic sulphur. Values for organic sulphur were obtained on extracts made using a soil : solution ratio of 1:20.

RESULTS AND DISCUSSION

In Table 1 the values obtained for total sulphur by three methods are reported. The values are expressed on air-dry soil basis. These results suggested that the fusion procedure was probably not achieving complete oxidation and that the gravimetric determination was not suitable for the amounts of sulphate being determined after an oxidation in the Parr bomb. Since the new method is relatively free from complications and appears to offer little opportunity for the loss of sulphur, during the procedure, it seems that results obtained by this method can be accepted with as much confidence as those obtained by other methods available at the time of writing.

Data are presented in Table 2 on the amounts of total sulphur and easily soluble sulphate in three Quebec soils studied, together with similar data quoted from Evans and Rost (4) and from Mann (15). The figures of Evans and Rost are mean values for 11 Minnesota podsols. Those of Mann were obtained on soil samples from the experimental plots at Woburn, England, which had been under continuous cultivation for 50 years.

The sulphur content of the Quebec podsols is significantly higher than that of the Minnesota podsols, but since the analytical methods employed were different, the higher levels for the Quebec podsols may be due, at least

TABLE 2.—TOTAL SULPHUR AND EASILY SOLUBLE SULPHUR

Soil	Total S in p.p.m.	Easily soluble sulphate		Analyst
		p.p.m. S	Per cent total S	
Woburn	45	3	7	Mann Evans and Rost Lowe Lowe Lowe
Podsols	100	8	8	
Sherbrooke (Pod.)	525	8	2	
Greensboro (Pod.)	440	10	2	
Grenville (Br. For.)	1385	14	1	

TABLE 3.—HUMUS SULPHUR AND ORGANIC SULPHUR

	Humus sulphur		Organic sulphur		Analyst
	p.p.m. S	Per cent total S	p.p.m. S	Per cent total S	
Woburn	9	21	15	33	Mann Evans and Rost Lowe Lowe Lowe
Podsols	23	23	50	50	
Sherbrooke (Pod.)	215	41	310	59	
Greensboro (Pod.)	176	40	308	70	
Grenville (Br. For.)	116	8	462	33	

TABLE 4.—SULPHUR EXTRACTED FROM THE GRENVILLE SOIL WITH VARIOUS REAGENTS
(Results expressed on air-dry basis)

Extractant	1st ext. p.p.m. S	2nd ext. p.p.m. S	3rd ext. p.p.m. S
Distilled water	5.0	2.5	1.6
0.001 N HCl	5.5	4.0	10.5
0.1 N HCl	8.5	3.2	3.3
1.0 N HCl	30.0	6.7	20.5
Morgan's solution	10.0	5.2	Not det'd.

in part, to more complete recovery of sulphur by the bomb method. It can also be noted that the easily soluble sulphate fraction is small for all soils cited.

Table 3 presents data on the organic sulphur fractions for the same soils.

These results indicate that the proportions of humus and of organic sulphur in the brown forest soil are apparently significantly lower than those of the podsols. These further differences between the Minnesota and Quebec podsols may also be due in part to the different methods employed. It can also be noted that the bicarbonate extractions removed more sulphur from the Quebec soils than the ammonium hydroxide extractions.

It should be pointed out, in this connection, that the values for organic sulphur obtained with the bicarbonate extraction might be expected to be low in view of the results of Johnson and Nishita (6) and of Freney (5). They have shown that in the reduction process involved in the methylene blue determination, there is no recovery of sulphur from such organic sulphur compounds as cystine, cysteine, methionine, taurine, sulphanilic acid and thiourea and that very low recovery is obtained with others including ethyl sulphide and glutathione. It can also be noted that for the Quebec soils only 34-72 per cent of the total sulphur was removed as easily soluble sulphur and organic sulphur. The nature of the sulphur not recovered is uncertain.

Some of the factors affecting the release of easily soluble sulphur from the Grenville soil were studied, in particular the effects of acid concentration, time of contact and temperature.

Table 4 presents amounts of this fraction removed by successive extractions with various reagents. The time of contact for the third extraction with each reagent was 6 hours.

The soil residue subjected to three extractions with 0.1 N HCl was extracted three more times with the same reagent, and the extracts were found to have removed 3.4, 3.2 and 3.3 p.p.m. S, air-dry soil basis, for the 4th, 5th and 6th extractions respectively. These figures indicate slow and steady release of easily soluble sulphur and a marked effect of acid concentration.

The effect of temperature was next investigated, using 0.1 N HCl as extractant. The amounts of sulphur recovered at 25°, 60° and 90°C. were 6.0, 20.5 and 24.0 p.p.m. respectively.

TABLE 5.—SULPHUR EXTRACTED BY CONCENTRATED HCl, IN A 10-MINUTE EXTRACTION AT 70°C.

Soil	Per cent total S extracted	Per cent ext'd. S sulphate form	S present as SO ₄ in p.p.m. soil
Sherbrooke	62	74	240
Greensboro	40	78	138
Grenville	36	44	220

These effects of time, temperature and acid concentration suggest the existence of a hydrolytic effect or perhaps solubility effect.

The results of these experiments on the easily soluble sulphur fraction suggested that considerable amounts of sulphur might be extracted by a short treatment with stronger HCl solutions, the more so since previous work in this laboratory (13) had shown that a high proportion of the total phosphorus of the Greensboro soil could be removed by a 10-minute treatment with concentrated HCl at 70°C. The latter treatment was then applied to the three soils under study, using a soil : acid ratio of 1:5. Under these conditions it was found that a high proportion (36-62 per cent) of the total sulphur of the three soils was extracted, and furthermore, that a high proportion (44-78 per cent) of the extracted sulphur was present in the sulphate form. The results of these determinations are given in Table 5.

To ascertain whether or not this sulphate sulphur was derived from organic combination, an extract obtained by successive treatment with the alkaline bicarbonate reagent and then with 2 per cent sodium hydroxide until no further colour was removed from the soil, was dialyzed to remove any free sulphate, then treated with 6 N HCl at 90°C. for 12 hours and the acidic supernatant solution, obtained on filtration, analysed for sulphate by the chloranilate method. It was found that about one-third of the sulphur in the solution was in the sulphate form. This result suggests strongly that sulphate sulphur is associated with the soil organic matter extracted with alkaline reagents, and that it can be released from the association by treatment with HCl. It was also noted that after such an exhaustive extraction with alkaline reagent as that just described, treatment of the soil residue with concentrated HCl at 70°C. for 10 minutes removed only traces of sulphur. This result suggests that the sulphur extracted by direct treatment with HCl, in the studies of the easily soluble sulphur fraction, might also be derived from the same organic materials extractable with alkaline reagents.

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MINERALOGY OF THE QUEENS LOAM AND QUEENS CLAY LOAM SOILS OF EASTERN NEW BRUNSWICK¹

S. W. REEDER², H. G. DION³ AND A. L. McALLISTER⁴

[Received for publication December 27, 1960]

ABSTRACT

On the basis of petrographic examination of the sand fraction and the X-ray diffraction, differential thermal, electron microscope, ethylene glycol retention, base exchange capacity and fusion analyses of the clay fraction it was concluded that these soils were developed on similar parent materials, were derived from common geological formations, and have been subjected to similar weathering and development processes since time of deposition.

INTRODUCTION

In the southeastern part of the province of New Brunswick a number of reddish brown clayey soils have developed on glacial till derived from predominantly non-calcareous material of Carboniferous age. When classified these soils were divided into a number of soil series with the Queens soil series predominating.

During the soil survey of this area the Queens soil series was divided into two textural types: the Queens loam and Queens clay loam. Since this time there has been considerable speculation as to whether these two soil types were textural variations of one soil series or whether the textural difference was actually an indication of a different type of parent material.

This investigation was initiated to study the mineralogy of these soils for the purpose of establishing their relationships or differences in order to determine whether they were properly classified as members of the same soil series. In addition, it was anticipated the investigation would give some indication of the effect of weathering on the genetic horizons of the two profiles.

DESCRIPTION OF THE AREA

The soils of the Queens series are found on undulating to gently rolling lowland in the southeastern part of the province (1); to a lesser extent in the northeastern part of the province; and to a very small extent on rolling to hilly upland at other scattered points.

The geology is described as Carboniferous which includes great thickness of conglomerate, sandstone, siltstone, shale and limestone. The thickness of the beds exceeds 16,000 feet (12). The section is characterized by "red beds" and in consequence a reddish coloured soil now covers the whole of the area.

The mean annual precipitation in the area is 40.7 inches; the mean annual temperature is 41.3°F.; and the average frost-free period is 133.2 days.

DESCRIPTION OF SOILS

The Queens series covers approximately 500,000 acres and occurs in moderately well-drained positions. It is commonly found with its poorly drained catenary associate, the Kings series, which covers approximately 300,000 acres (1).

¹Contribution from the New Brunswick Soil Survey, Canada Department of Agriculture, Research Branch. Based on M.Sc. thesis submitted by the senior author to McGill University, 1956.

²Formerly Pedologist, New Brunswick Soil Survey, Fredericton, N.B., on study leave at the Department of Agricultural Chemistry, Macdonald College, Quebec; now Assistant Research Officer, Earth Science Branch, Soils Division, Research Council of Alberta, Edmonton, Alta.

³Vice-Principal and Dean, Faculty of Agriculture, Macdonald College, Quebec.

⁴Associate Professor of Geology, University of New Brunswick, Fredericton, N.B.

These soils occupy the slopes of low knolls, ridges and river basins. The topography varies from undulating to gently rolling with the average slopes between $2\frac{1}{2}$ and $7\frac{1}{2}$ per cent.

The Queen's series includes two soil types — the loam and clay loam, of which the loam is more extensive. Profile descriptions for the area studied are presented below:

Queens Loam

<i>Horizon</i>	<i>Depth, inches</i>	<i>Description</i>
A _o (L-H)	2-0	Partially decomposed roots and mixed forest litter; pH 4.3.
A ₂ (Ae)	0-3	Pinkish grey (5YR 6/2, moist) loam; medium to fine crumb; moderately firm; pH 4.5.
B ₂ (Bir)	3-8	Dark brown (7.5YR 4/4, moist) loam; fine crumb; friable with a loose consistency; pH 5.0.
B ₂ (BC)	8-14	Dark reddish brown (5YR 3/4, moist) loam; medium crumb; moderately firm; pH 5.2.
C ₁	14-26	Dark reddish brown (5YR 3/3, moist) clay loam; medium blocky; firm; pH 5.4.
C ₂	26-32	Dark reddish brown (5YR 3/3, moist) clay loam; medium blocky; firm; pH 5.4.

Stoniness — Moderately stony

Slope — 1 per cent

Elevation — 220 feet

Location — Three miles west of Havelock on the Salem road

Vegetation — Grey and white birch, red maple, poplar, fir, red and white spruce

Classification — Podzol.

Queens Clay Loam

<i>Horizon</i>	<i>Depth, inches</i>	<i>Description</i>
A _o (L-H)	2 0	Partially decomposed mixed forest vegetation and roots; pH 4.3.
A ₂ (Ae)	0-3	Pinkish grey (5YR 6/2, moist) loam; medium to fine crumb; firm; pH 4.4.
B ₂ (Bir)	3-8	Brown (7.5YR 5/4, moist) clay loam; medium to coarse crumb; firm; pH 5.2.
B ₂ (BC)	8-12	Reddish brown (5YR 4/3, moist) clay loam; coarse crumb; firm; pH 5.5.
C ₁	12-24	Dark reddish brown (5YR 3/3, moist) clay; medium blocky; firm; pH 5.5.
C ₂	24-30	Dark reddish brown (5YR 3/3, moist) clay; medium blocky; firm; pH 5.5.

Stoniness — Moderately stony

Slope — 1 per cent

Elevation — 172 feet

Location — Five miles west of Havelock on the Salem road

Vegetation — Grey and white birch, red maple, poplar, fir, red and white spruce

Classification — Podzol.

EXPERIMENTAL METHODS

The sampling locations were chosen to conform, as nearly as possible, to the description as laid down for the Queens series (1).

Bulk and core samples were carefully taken of the genetic horizons. The bulk samples were air dried, crushed, screened through a 2-mm. sieve and thoroughly mixed. The required amounts for analyses were taken by the quartering method. The core samples were dried to constant weight at 105°C., cooled, weighed, and the bulk density determined. Duplicate 2-gram samples of the prepared soil were dried to constant weight at 105°C. and the hygroscopic moisture determined.

Mechanical Analysis

The mechanical composition of the samples was determined by the Bouyoucos hydrometer method (3). The sand was separated from the silt and clay by wet sieving. The silt was separated from the clay by repeated centrifugings. The sand fraction was further separated by dry sieving into three fractions, 2.00 to 0.25 millimetres, 0.25 to 0.10 millimetre and 0.10 to 0.05 millimetre. The clay fraction was separated into two fractions, 2 to 1 micron and <1 micron, using the Sharples supercentrifuge and the formula as given by Bayer, page 38 (2).

Mineralogical Analysis

Sand Fraction — The free oxides of iron and aluminium on the sand grains were removed with warm dilute HCl before separating into specific gravity separates.

The sand fractions were further separated into specific gravity separates > 2.95 and < 2.95, using mixtures of s-tetrabromoethane and nitrobenzene and following the procedure of Volk (30). The specific gravity separates were mounted on glass slides using gelatin (17) and the minerals identified by petrographic methods (9, 20). The feldspars were identified by chemical staining procedures (23).

< 1 Micron Clay Fraction — The clays from the mechanical separations were flocculated by adding NaCl, washed free of chlorides with ethanol using the centrifuge, and dried at 60°C. The iron oxide coating was removed using the method proposed by Mitchell and MacKenzie (21). The clays were prepared for X-ray analysis using the glycerol solvation procedure of White and Jackson (31) and determined by means of a Geiger counter X-ray spectrometer (15). Differential thermal analysis were made using an apparatus built by the Physics Department, Macdonald College. The heating rate was 10°C. per minute, controlled by an electronic program controller. The electron microscope used for the determination was a table model with a magnification of 6,000 times. Specimen screens were prepared according to the procedure of Humbert and Shaw (14).

The method proposed by Martin (18) was used for the ethylene glycol retention analysis. Base exchange capacity was determined using the method proposed by MacKenzie (16). The loss on ignition was determined at 850°C. Sodium carbonate fusion was done by the method of Corey and Jackson (7). Silica was determined colorimetrically with ammonium molybdate (7). Iron was determined colorimetrically with potassium cyanide (13). Aluminium was determined colorimetrically using the aluminon method (24) on the same solution as for iron. Potassium and

magnesium were determined by flame photometry (7). Soluble silica and alumina were extracted by adding 100 millilitres of water containing 5 grams of sodium carbonate to 1 gram of sample and boiling for 5 minutes. The determinations were made colorimetrically (7, 24).

RESULTS AND DISCUSSION

Mechanical Analysis

The results of the mechanical analysis of the 2-mm. soil separates are given in Table 1. These results show that the parent material of the Queens clay loam soil is somewhat finer in texture than the parent material of the Queens loam soil. This textural difference is also reflected in the B horizons. The data show a gradual increase in clay content with depth, except between the A₂ and B₂ horizons where a distinct textural break is evident in both soils. An explanation for this textural difference would be no more than speculation at this time. However, it is interesting to note that both soils show similar amounts of clay-size particles in their A horizons.

TABLE 1. — VOLUME WEIGHT AND MECHANICAL COMPOSITION OF THE SOILS EXPRESSED AS PER CENT WEIGHT ON AN OVEN-DRY BASIS

Soil series	Horizon	Volume weight of whole soil	2.0-0.25 mm. sand	0.25-0.10 mm. sand	0.10-0.05 mm. sand	Total sand	Silt	Clay	Texture
Queens loam	A ₂	1.27	21.0	15.3	12.6	48.9	35.9	15.2	L
	B ₂	1.21	19.1	13.4	9.4	41.9	33.4	24.7	L
	B ₃	1.67	20.0	12.7	9.3	42.0	32.5	25.5	L
	C ₁	1.77	18.2	11.3	9.0	38.5	30.9	30.6	CL
	C ₂	1.76	16.9	10.9	6.7	34.5	31.2	34.3	CL
Queens clay loam	A ₂	1.18	16.4	11.4	9.5	37.3	47.0	15.7	L
	B ₂	1.10	14.4	8.8	7.7	30.9	38.8	30.3	CL
	B ₃	1.48	11.7	7.8	7.3	26.8	36.9	36.3	CL
	C ₁	1.71	10.7	5.8	7.9	24.4	36.4	39.2	CL
	C ₂	1.70	10.2	5.3	7.7	23.2	34.6	42.2	C

L-Loam, CL-Clay loam, C-Clay

TABLE 2. — SPECIFIC GRAVITY SEPARATES EXPRESSED AS PER CENT BY WEIGHT OF THE 0.10- TO 0.05-MM. SAND FRACTION

Queens loam			Queens clay loam		
Horizons	Heavy minerals >2.95	Light minerals <2.95	Horizons	Heavy minerals >2.95	Light minerals <2.95
A ₂	1.8	98.2	A ₂	1.6	98.4
B ₂	0.9	99.1	B ₂	1.0	99.0
B ₃	1.0	99.0	B ₃	1.4	98.6
C ₁	1.1	98.9	C ₁	1.6	98.4
C ₂	1.1	98.9	C ₂	1.7	98.3

A very interesting fact revealed by the data was that the B₁ horizons of both soils had the least volume-weight of all the horizons. This difference in volume-weight may be attributed to weathering processes within the profiles because it was shown for both soils that the volume-weight of these horizons was considerably less than the volume-weight of their parent materials.

Mineralogical Analysis

Sand Fraction — The results of the specific gravity separates of the 0.10- to 0.05-mm. sand fractions of both soils are presented in Table 2. Only the results for 0.10- to 0.05-mm. sand fraction were presented because they were found to be the most representative.

The data show that approximately 98 per cent of the minerals of these soils have specific gravities < 2.95. The minerals of this lighter fraction present a much less variety than those of the heavier fraction (> 2.95). However, they consist of at least two important groups, the micas and quartz-feldspar groups. Present knowledge concerning the occurrence of changes in composition of these minerals brought about by weathering agencies is insufficient, but for purposes of correlation the amounts of these minerals may give some idea as to the origin and transportation process in soil development, when combined with other supporting evidence.

The remaining 2 per cent of the minerals of these soils have specific gravities > 2.95. The minerals of this specific gravity fraction were shown to contain a much greater variety of mineral species than the lighter fraction. Because of the greater variety of mineral species usually present in this fraction most of the efforts of workers in geology and soil mineralogy have been concentrated on this small but important specific gravity separate.

Numerous attempts have been made to arrange minerals in order of their resistance to weathering (22, 28, 10, 8) but these independent estimates contain significant differences in order of resistance. The differences can be attributed mostly to geographical location and origin. However, it is generally considered that zircon and tourmaline are stable under any weathering conditions (5, 27, 10, 29, 25, 26, 28). It has also been shown that epidote and hornblende are common in practically all soils (19), and that podzolization caused some reduction in hornblende, whereas zircon, tourmaline, epidote and garnet were little affected (6).

The results of the mineral proportions in the Queens soils (Table 3) show that epidote, tourmaline, zircon and garnet decreased in quantity with depth conforming to the findings of Cody (6) for Podzol soils. The iron oxide minerals, amphiboles and pyroxenes, on the other hand, increased with depth indicating a reduction in quantity in the upper horizons brought about by the severe weathering conditions in existence in the Podzol soil zone. A detailed study of the minerals of the sandstones of the underlying geological formations showed the same minerals to be present as identified in these soils.

From the results of Table 3 weatherable and resistant ratios for the heavy mineral fraction, specific gravities > 2.95, were set up as shown in Table 4.

TABLE 3. — MINERAL PROPORTIONS OF SPECIFIC GRAVITY SEPARATES IN THE 0.10 - TO 0.05 - MM. SAND FRACTION
(Expressed as numerical percentage of total grains present in each separate)

Series	Horizon	Specific gravity > 2.95							Specific gravity < 2.95			
		Iron oxide minerals	Amphiboles & pyroxenes	Epidote	Tourmaline	Zircon	Garnet	Others	Quartz	Micas	Feldspars	
Queens loam	A ₂	6.91	32.99	32.86	1.98	5.58	0.28	19.40	99.68	0.26	0.18	
	B ₂	4.74	32.61	37.01	1.59	2.24	0.25	21.56	99.53	0.26	0.21	
	B ₂	9.80	35.56	28.77	1.32	2.60	0.23	22.72	99.51	0.24	0.25	
	C ₁	10.20	40.55	18.32	1.10	1.17	0.20	28.46	99.47	0.20	0.33	
	C ₂	12.83	40.22	11.59	1.02	1.12	0.14	33.08	99.44	0.16	0.40	
Queens clay loam	A ₂	7.51	32.53	32.08	2.08	5.42	0.26	20.12	99.68	0.23	0.09	
	B ₂	5.34	31.69	37.21	1.69	2.31	0.27	21.49	99.65	0.21	0.14	
	B ₂	8.78	36.16	28.81	1.30	2.62	0.21	22.12	99.62	0.18	0.20	
	C ₁	10.73	40.22	17.20	1.00	1.17	0.23	29.45	99.57	0.14	0.29	
	C ₂	12.64	40.20	11.45	0.82	1.16	0.10	33.63	99.57	0.11	0.32	

These ratios were established on the basis of percentage counts of those mineral species shown to be unaffected by podzolization which comprised zircon, tourmaline, garnet, and epidote, and the percentage counts of those mineral species shown to be affected which consisted of amphiboles, pyroxenes, and the iron oxide minerals.

The ratios for the light mineral fraction, specific gravities < 2.95 , were not established for these soils because 99 per cent of the mineral species of this fraction was quartz and, therefore, the ratios would have been of little significance. However, ratio for this fraction may be established by using feldspars and micas as the weatherable mineral species and quartz as the resistant mineral species.

The data indicate pronounced similarity of the species and quantity of minerals found to be present in these soils. The ratios show an orderly decrease with depth, except the B₂ horizons which show the largest ratio indicating these horizons were the most seriously affected by weathering agencies. This effect was substantiated by a loss in volume-weight as illustrated in Table 1.

The mineralogical nature of the sand fractions of these soils was shown to be similar between the two soil types, as well as that of the parent materials, the characteristics of which were inherited from the underlying geological formations.

Clay Fraction — X-ray diffraction, differential thermal and electron microscope procedures indicated that the clay fractions from the two soil types were mineralogically similar as in the case of the sand fractions.

TABLE 4. — ABUNDANCE OF RESISTANT AND WEATHERABLE HEAVY MINERALS IN THE 0.10- TO 0.05-MM. SAND FRACTION

Series	Horizons	Per cent ¹		R:W ⁴
		Resistant ²	Weatherable ³	
Queens loam	A ₂	40.70	39.90	1.02
	B ₂	41.09	37.35	1.10
	B ₃	32.92	44.36	0.74
	C ₁	20.79	50.75	0.41
	C ₂	13.87	53.05	0.26
Queens clay loam	A ₂	39.84	40.04	0.99
	B ₂	41.48	37.03	1.12
	B ₃	32.94	44.94	0.73
	C ₁	19.60	50.95	0.38
	C ₂	13.53	52.84	0.25

¹Percentages by count under the petrographic microscope

²Zircon, tourmaline, garnet and epidote

³Amphiboles, pyroxenes and iron oxide minerals

⁴Zircon + tourmaline + garnet + epidote

Amphiboles + pyroxenes + iron oxide minerals

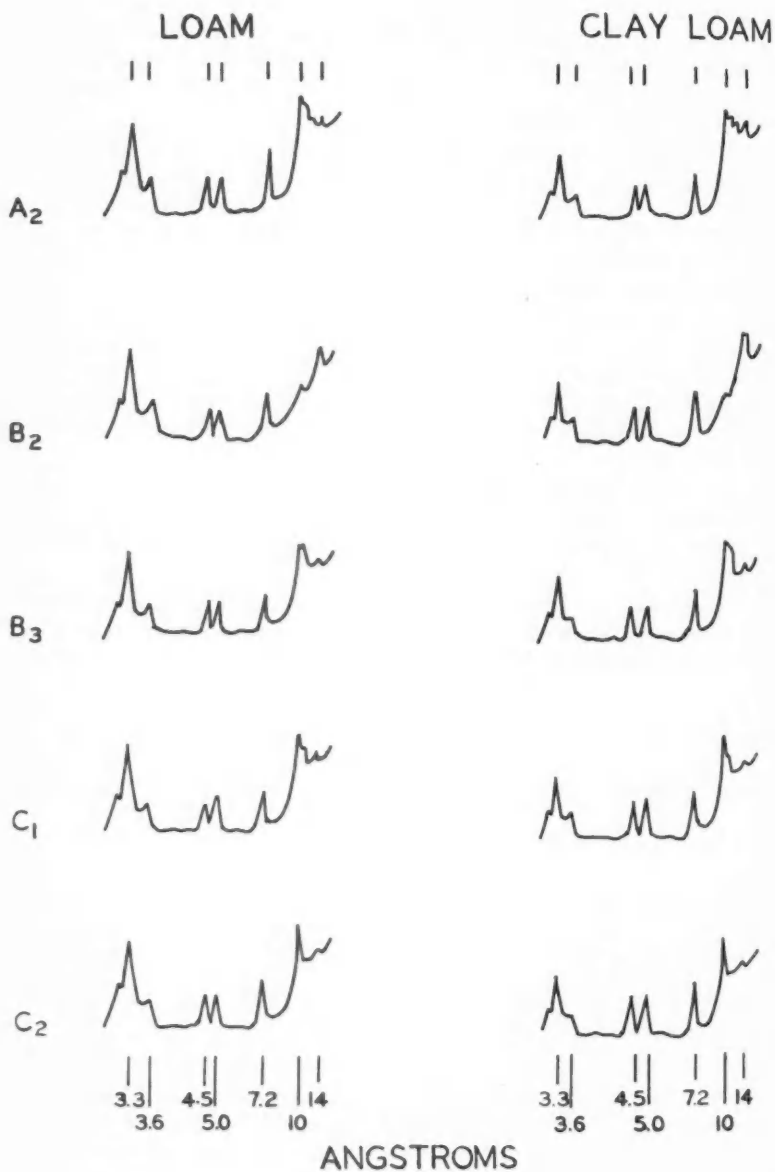


FIGURE 1. X-ray diffraction patterns of Queens soils 0.001-mm. clay fraction. Glycolated.

TABLE 5. — CHEMICAL ANALYSIS OF THE CLAY FRACTION (0.001-MM.) OF THE QUEENS SOILS

Soil series	Horizons	% Hyg. moisture	% Loss on ignition	% SiO_2 ¹	% Al_2O_3 ¹	% Fe_2O_3 ¹	% MgO	% K_2O	Total oxides	E.C. m.e./100gm.	Glycol retention mgm./gm.
Queens loam	A ₂	1.51	8.76	58.21	26.08	1.67	0.48	3.89	100.60	50.76	145.8
	B ₂	2.19	7.73	57.04	25.65	2.31	1.13	5.20	101.25	57.06	110.1
	B ₃	1.15	8.48	58.90	23.40	2.31	0.33	5.15	99.72	52.20	134.2
	C ₁	1.33	7.79	58.62	23.92	2.17	0.45	5.10	99.38	44.10	140.0
	C ₂	1.82	8.30	58.09	24.88	2.09	0.33	5.05	100.56	38.70	149.1
Queens clay loam	A ₂	1.74	6.93	54.20	31.11	1.24	0.56	4.12	99.90	48.60	153.5
	B ₂	2.27	7.54	52.04	31.25	1.72	1.13	4.36	100.31	54.00	109.8
	B ₃	1.77	6.39	53.06	32.10	1.36	0.56	4.30	99.54	51.30	113.8
	C ₁	2.15	6.91	51.98	32.10	1.32	0.73	4.87	100.06	41.76	133.4
	C ₂	2.33	6.98	52.37	32.33	1.31	0.56	5.00	100.88	37.80	157.0

¹Calculated on a SiO_2 , Al_2O_3 and Fe_2O_3 soluble-free basis

X-ray Results — Patterns of the oriented specimen of the < 1 micron clay-size fraction (Figure 1) from each horizon of the Queens loam and Queens clay loam soils revealed that the clay-size minerals were very similar and showed similar weathering effects. The patterns of the glycolated specimen showed reflections at 14, 10, 7.2, 5.0, 4.5, 3.6, 3.33 and 3.21 to 3.25 Å indicating the presence of chlorite, illite, kaolinite and feldspars (11). Upon heating to 500°C. the orders of illite basal spacings at 10.5 and 3.33 Å and the chlorite basal spacings at 14 and 4.7 persisted (4) but the 7.2 and 3.6 Å reflections were considerably weakened, indicating kaolinite contributed to the 7.2 Å feature in addition to chlorite. The reflection for feldspars remained at 3.21 to 3.25 Å.

The series of diffraction maxima between 10 and 13 Å, shown as a broadening of the 10 Å reflection, was considered to be the result of weathering of the illite units (degrading illite). This displacement of the 10 Å reflection gives a good indication of the degree of weathering in the various horizons. It can be seen that the broadening of the 10 Å reflection decreased with depth and with the B₂ horizons of both soils showing the greatest effects. This effect further substantiates the findings as revealed in the sand fractions for the B₂ horizons of both soils.

Differential Thermal Results — The differential thermal patterns for both soils (Figure 2) show a predominance of 2:1 layer lattice clay-size minerals, unidentifiable as to species. The patterns were very similar for all horizons which indicates a similarity of mineralogical constitution.

Electron-microscope Results — The electron micrographs showed the clays of both soils to consist of thin tubular crystals with regular outlines, and irregular aggregates made up of very small crystals of a mica-like nature. This corroborates the findings from X-ray analysis and further substantiates the presence of the illite clay mineral.

Chemical Results of Clay Fraction — The data for the chemical analysis of the < 1 micron clay-size fraction for these soils, Table 5, show a uniformity of at least the major mineral constituents of the clay minerals within and between soil types. The MgO content corroborates the presence of chlorite, and the K₂O content indicates appreciable amounts of illite. The base-exchange capacity values were relatively high and were higher than would be expected if an appreciable amount of kaolinite was present. Ethylene glycol retention values, although variable, indicate the presence of appreciable amounts of illite, the illite usually being considered to have a range of 80 to 200 milligrams per gram of clay.

Combining the data obtained by the foregoing analyses, the following conclusions may be made: The mineralogy of the loam and clay loam soils of the Queens series was similar throughout the profiles, in the parent materials and in the underlying geological formations, indicating these soils were developed on similar parent materials and derived from common geological formations. The data also indicate the soils have been subjected to similar weathering and development processes since time of deposition. The B₂ horizons of both soil types showed evidence of containing the most

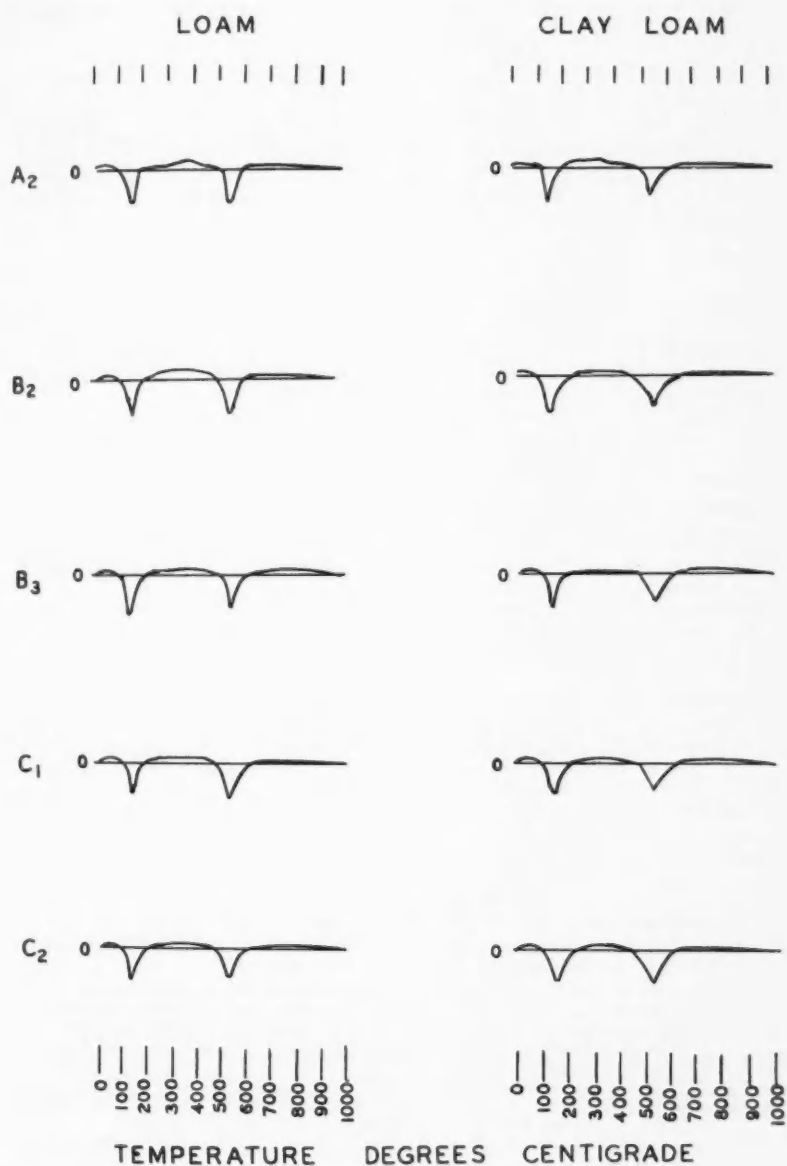


FIGURE 2. Differential thermal curves of Queens soils 0.001-mm. clay fraction.

seriously affected constituents as a result of the weathering and development processes present in the Podzol soil zone.

ACKNOWLEDGEMENTS

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ALTERNATE FREEZING AND THAWING NOT A REQUIREMENT FOR FROST HEAVING IN SOILS

E. PENNER¹

National Research Council, Ottawa, Ontario

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ABSTRACT

Field measurements of frost heaving beneath a cold storage plant and laboratory soil freezing experiments in "open" and "closed" systems support the view that both a freezing and thawing cycle are *not* required for frost heaving as has been suggested in a recent paper (2).

INTRODUCTION

In a recent paper (2), giving results from heaving experiments in the field, it was intimated that freezing and thawing are "required" for frost heaving, whereas in the summary the suggestion was made that freezing and thawing "favour" frost heaving in field plots.

These statements appear to be contradictory and are not consistent with well-established facts in the literature about the frost action process (3). The writer is not so much concerned with the contradiction, however, as with the statement about the "requirement" for frost heaving. The purpose of this paper is to present evidence to show that the frost heaving process is not contingent on the presence of a thawing cycle either in laboratory experiments or in the field.

THEORY OF FROST HEAVING

Frost heaving in soils is the result of ice lensing. An ice lens obtains water for growth by drying the soil in its vicinity, thereby creating a suction gradient in the water of the unfrozen soil. At the same time, sufficient additional energy is made available in the water-ice phase change to lift the frozen soil. Frost heaving will only occur, however, if sufficient water is available, the soil temperature is below 0°C., and the soil is frost susceptible, i.e., a soil which supports ice lens growth.

Another condition must also be met. During the water-ice phase change the latent heat of crystallization must be removed in order to sustain heaving. This provides a convenient means of following the progress of ice formation. In the particular case of a stationary freezing front the amount of heave may be computed from the net heat extraction.

To a large extent, the rate of heat removal determines the rate of heaving. This has been shown to hold for soils of widely different characteristics in laboratory experiments (4); when heat removal becomes excessive, however, the permeability of soil may limit the rate of frost heaving.

RESULTS AND DISCUSSION

Laboratory Experiments

The results of a laboratory freezing experiment with Leda clay at two rates of heat extraction are shown in Figure 1. In particular it should be noted that the heat flow was in one direction in both stages 1 and 2 of the experiment, i.e., there was no thawing cycle. The rate of heaving

¹Research Officer, Division of Building Research, National Research Council, Ottawa, Ont.

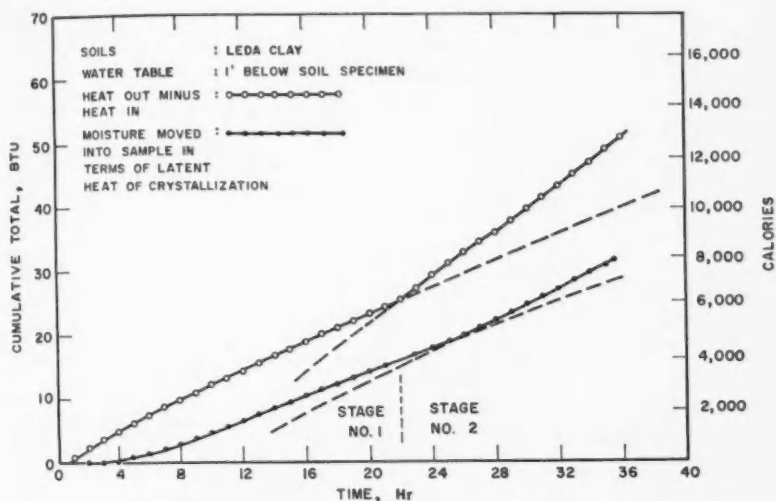


FIGURE 1. Cumulative values of net heat flow and moisture flow vs. time.

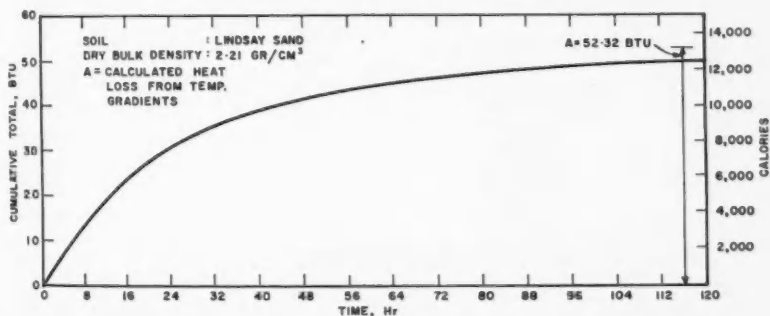


FIGURE 2. Net difference between heat out and heat in as a function of time in a closed system as measured by heat meters.

during stage 1 was about 1.5 inches per day; during stage 2 it was 2 inches per day. Calibrated heat flow meters, 6 inches in diameter, were placed at each end of the 3-inch-high soil specimen to measure the heat flow. Water was supplied from an automatic balance arrangement at a suction equivalent to 1 foot of water. Both heat and water flow were continuously recorded on a millivolt recorder.

The results (Figure 1) show that a steady rate of heat flow in an "open system" can produce very substantial frost heaving. This is also true if the system is allowed to desaturate, "closed system". The heat removed during freezing can be accounted for in terms of the latent heat of fusion of the water frozen and the cooling of the sample. Figure 2 gives net heat flow

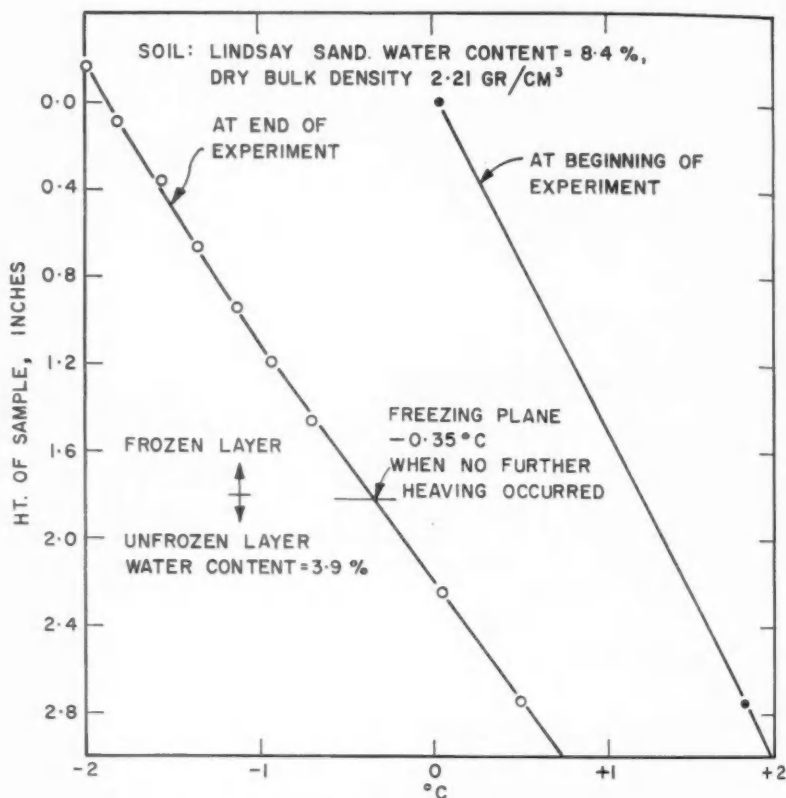


FIGURE 3. Temperature distribution at equilibrium in closed system.

measured by heat flow meters as a function of time for a closed system. Figure 3 shows the temperature gradient before heaving began and after heaving ceased. The sample was saturated before freezing commenced and no further water was supplied during the freezing period. Again, a smooth and continuous heat flow in one direction during the experiment may be noted.

In the unfrozen portion, the water content had been reduced from the saturated state of 8.4 per cent to 3.9 per cent. From the known unfrozen water-temperature relationship for the soil, the amount of ice in the frozen portion could be estimated. The difference between heat in and heat out measured by the heat meters was 49.8 B.t.u. Freezing of the water took 47.6 B.t.u. and cooling the soil, water and ice took 4.8 B.t.u. This leaves only 5 per cent of the heat extracted unaccounted for, a good balance when the difficulties in doing the many experiments to permit such a computation are considered.

Field Measurements

Level surveys carried out on the floor of a cold storage plant at Cornwall, which was subjected to extensive frost heaving damage after 8 years of continuous operation, showed frost heaving was still in progress (1). For the period February to June, the frost line penetrated from 8 to 9 feet, resulting in some 2½ inches of heaving in the centre of the building. This situation represents frost heaving in the field but compares, in its steady unidirectional heat removal, to the laboratory experiments described.

CONCLUSION

It is believed that sufficient experimental evidence has been provided to conclude that alternating freezing and thawing is not a "requirement" for frost heaving.

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SULPHUR FRACTIONS OF LEGUMES AS INDICATORS OF SULPHUR DEFICIENCY¹

D. R. WALKER² AND C. F. BENTLEY³

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ABSTRACT

A study of 157 locations, representing 18 soil series in west central Alberta, revealed that yield responses of alfalfa, alsike clover and red clover to applications of sulphur fertilizer were not confined to either specific soil series or definite geographical areas.

Samples of the three legume crops from 74 of the test locations were analysed to determine the usefulness of three sulphur fractions and of the ratio total nitrogen:total sulphur as indicators of the need for sulphur fertilization. Extractable sulphur and extractable sulphate were present in considerably larger quantities in alfalfa and alsike clover grown on non-sulphur-deficient soils as compared with samples from soils deficient in that element. These determinations offer a possible means of detecting the need for sulphur fertilization with those two legume crops. While total sulphur and the total nitrogen-total sulphur ratio also showed differences, their magnitude was not of the same order as with these two fractions.

Similar determinations for red clover showed the differences to be smaller than for alfalfa and alsike clover and they appear to be of doubtful value for predicting the need for sulphur fertilization.

INTRODUCTION

Sulphur deficiency has been rather widely reported in North America (2, 4, 8). In Alberta the occurrence of sulphur-deficient soils has been known for nearly 30 years and a considerable amount of work on the management of such soils has been done (9). To date no generally accepted test for the accurate and convenient identification of sulphur-deficient soils has been reported, although many procedures have been tried (2, 3, 7, 10, 11). Plant analyses which have shown promise for the detection of sulphur-deficiency in soils include: sulphate-sulphur; total sulphur; and ratio of total nitrogen to total sulphur (1, 3, 10). A test method involving the growth of *Aspergillus niger* on soil has also been described (7, 11).

The present study was undertaken to determine the frequency and pattern of sulphur-deficiency in an area of west central Alberta and to determine the effectiveness of various analytical procedures as methods to detect the need for sulphur fertilization of crops growing in that region.

MATERIALS AND METHODS

Field Tests

During 1957 and 1958 spring applications of fertilizer grade sodium sulphate, supplying 20 pounds per acre of sulphur, were made on 157 locations involving 18 different series of chernozemic and podzolic soils in that part of Alberta bounded by Leduc, Breton, Sundre and Olds, an area of approximately 3,000 square miles. Sulphur deficiency was known to be common in podzolic soils in this area but the proportion of the area and of specific soil series which were sulphur-deficient was unknown. At each location a 4 square-rod area of previously unfertilized legume crop was treated with sodium sulphate. Assessment of response was made

¹Contribution from Research Branch, Canada Department of Agriculture, and the Department of Soil Science, University of Alberta, Edmonton, Alta.

²Agronomist, Research Station, Lacombe, Alta.

³Professor of Soil Science.

TABLE 1.—ANALYTICAL DATA FOR FERTILIZED AND UNFERTILIZED LEGUMES GROWN IN 1957 AND 1958. FIGURES SHOWN ARE AVERAGED WITH ACCOMPANYING STANDARD DEVIATIONS

	No. samples analysed	No sulphur applied						Sulphur applied at 20 lb./acre					
		Extract SO ₄ %*	Extract S %*	Total S %	Total N %	N/S ratio		Extract SO ₄ %*	Extract S %*	Total S %	Total N %	N/S ratio	
ALFALFA													
1957 sulphur-deficient	8	.04±.022	.13±.056	.16±.074	3.26±.331	19.8±1.06		.23±.093	.23±.069	.27±.061	3.76±.646	12.6±1.33	
1958 sulphur-deficient	10	.03±.021	.10±.032	.15±.038	2.88±.316	19.4±3.73		.24±.067	.29±.130	.26±.104	3.14±.456	12.2±2.85	
1958 non-sulphur-deficient	10	.19±.080	.30±.080	.24±.039	2.95±.190	12.8±2.48		.25±.055	.38±.105	.27±.030	2.97±.276	11.5±1.28	
ALSIKE CLOVER													
1957 sulphur-deficient	7	.02±.003	.06±.005	.10±.013	1.91±.317	19.3±1.99		.09±.029	.10±.035	.15±.024	2.37±.418	16.0±1.34	
1958 sulphur-deficient	9	.02±.005	.05±.016	.13±.016	2.60±.187	20.4±2.37		.22±.023	.29±.154	.25±.049	3.42±.374	13.8±1.41	
1958 non-sulphur-deficient	5	.08±.035	.16±.044	.19±.016	2.81±.168	15.3±2.09		.17±.080	.23±.057	.22±.057	3.03±.347	13.5±1.35	
RED CLOVER													
1957 sulphur-deficient	7	.05±.007	.05±.019	.09±.023	1.86±.239	20.6±2.76		.12±.027	.11±.033	.14±.027	1.99±.383	14.6±1.55	
1958 sulphur-deficient	10	.04±.013	.05±.019	.11±.019	2.46±.295	22.0±1.80		.08±.029	.15±.049	.19±.029	3.20±.531	16.5±1.26	
1958 non-sulphur-deficient	8	.05±.012	.09±.021	.18±.020	3.20±.420	18.3±0.62		.07±.012	.13±.024	.19±.016	3.19±.274	16.9±.084	

*Expressed as sulphate

visually and those sites having unquestionable yield increases from the sodium sulphate application were classified as sulphur-deficient.

In 1957 botanically pure composite samples of legume plants were collected for laboratory analysis from fertilized and unfertilized areas at test-sites where response to sulphur fertilization was obtained. The samples were harvested either late in July or from the second growth in early September. During 1958 samples were taken from sites not responding to sulphur fertilization as well as from sites where yield increases were obtained. The 1958 samples were all obtained early in July. Because of variations in soil texture, topography and moisture supply at different locations, the stage of maturity ranged from less than 10 per cent blossom to almost full blossom at sampling time. Plant samples were air-dried immediately after harvest and were oven-dried at 205°F. before laboratory analysis.

Laboratory Analyses

Plant samples were subjected to several analyses. Total sulphur was determined turbidimetrically by the method outlined by Bentley *et al.* (2) after ashing by the nitric-perchloric acid procedure (6). Total nitrogen was determined by the Kjeldahl-Gunning method (12). Two 10-minute extractions employing a 25:1 ratio of extractant to sample were made with 25-millilitre portions of 70 per cent ethanol in a blender. After a measured portion of this extractant had been decolorized with Norit "A" carbon black, barium chloride was added to precipitate the sulphate hereafter referred to as "extractable sulphate". In another portion of the alcoholic extract all sulphur was oxidized to sulphate with nitric-perchloric acids and the resulting ash was taken up in 0.1 N HCl for turbidimetric determination of what is hereafter referred to as "extractable sulphur". The procedure for extracting these fractions was a modification of the method used by Eaton (5).

RESULTS AND DISCUSSION

Yield responses to sodium sulphate application were clearly evident at 72 of the 157 test locations. Yield increases were variable and did not follow a geographical pattern. Moreover, the results were not uniform within soil series as only 5 of 18 series had no increases and for the remaining series the proportion of sites with yield increases ranged up to 67 per cent. Yield increases were not entirely restricted to the podzolic soils as four chernozemic soils also responded to the fertilization.

Analytical data for the plant analyses are presented in Table 1. The data reveal that extractable sulphur and extractable sulphate remained at low levels in alsike clover and alfalfa plants when the soil supply of that element was inadequate. If available soil sulphur was adequate to meet plant requirements, or when fertilizer sulphur was applied, the amounts of these two sulphur fractions in the plants were much greater. These relationships are well illustrated in Figure 1. Two alfalfa samples from sites not responding to the fertilizer application had rather small amounts of extractable sulphur and extractable sulphate. These locations were probably on the border-line of sulphur deficiency.

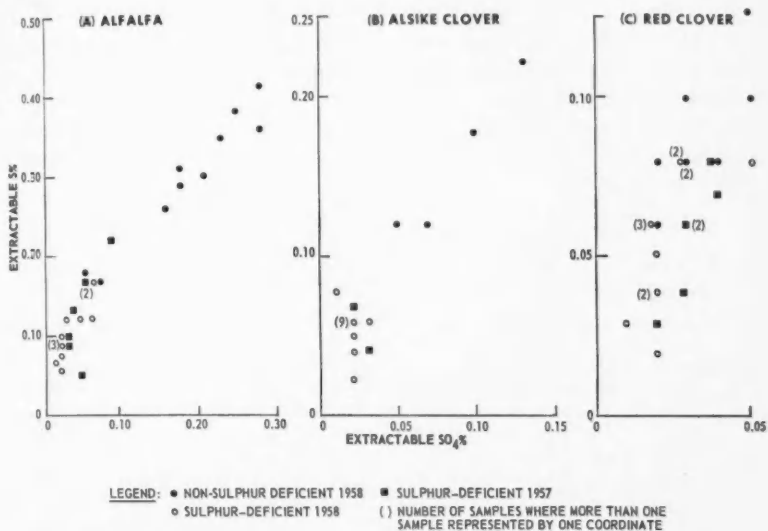


FIGURE 1. Extractable sulphur and sulphate content of unfertilized legume samples from sulphur-responsive and non-responsive soils.

For alfalfa and alsike clover the amounts of total sulphur followed trends which were generally similar to those for extractable fractions of that element but with smaller differences. The N:S ratios for alfalfa and alsike clover (Table 1) are similar to those reported by Bardsley and Jordan (1) for alfalfa.

The extractable sulphate content of red clover samples was less clearly influenced by the available sulphur status of the soil. Extractable sulphur, total sulphur and N:S ratio data for red clover samples followed trends similar to those observed for alfalfa and alsike clover but the differences were much less marked except in the case of total sulphur.

SUMMARY

The data reported herein indicate that extractable sulphur and extractable sulphate may provide reasonably satisfactory methods for ascertaining whether stands of alsike clover or alfalfa are in need of sulphur fertilization. For those crops the need for such fertilization is less clearly indicated by the total sulphur content or the N:S ratio. The data for determinations on red clover followed trends similar to those obtained with alfalfa and alsike clover but the differences were not of sufficient magnitude to use the analyses for determining the need for sulphur fertilization of this crop.

The results presented in this report indicate the desirability of further investigation of plant sulphur fractions as a means of determining the need for fertilization with that element.

ACKNOWLEDGEMENTS

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The assistance of T. W. Peters, Alberta Soil Survey, Canada Department of Agriculture, University of Alberta, in identifying the soils involved is acknowledged.

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MINERALOGY OF CHAMPLAIN SEA SEDIMENTS AND A RIDEAU CLAY SOIL PROFILE¹

J. E. BRYDON AND L. M. PATRY

Canada Department of Agriculture, Ottawa, Ontario

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ABSTRACT

Marine clays and silts of the Champlain Sea, or "Leda clays", from several locations in the Ottawa and St. Lawrence Valleys, and a Rideau Clay soil profile developed on this material have been examined. Although the textures of the marine sediments varied, there was a remarkable similarity in the nature of the mineral constituents of the sands, silts and clays; feldspars, quartz, amphiboles, micas, and chlorites occurred in all size fractions. In addition, the clay fractions contained small amounts of montmorillonite and interstratified illite-montmorillonite. All but two of the marine samples were slightly calcareous and, in general, the coarser textured materials contained the highest carbonate content. The main source of the deposits is believed to be the igneous and metamorphic rocks of the Canadian Shield, and there is very little evidence of weathering before, during and since deposition.

The Rideau Clay is a moderately well-drained regosolic soil with very little difference in exchangeable cations or mineral composition with depth. The occurrence of illuviation could not be shown conclusively because of apparent depositional differences. The Rideau Clay differed from the marine materials in having no carbonates, in being slightly acid throughout, and in having a greater amount and a different type of interstratified clay minerals.

INTRODUCTION

The Rideau Clay is a moderately well-drained regosolic soil occurring on marine clays and silts of the Champlain Sea which are often called "Leda Clay".² The exact geological history of these deposits is obscure and subject to disagreement. However, the work of Johnston (9), Antevs (2), Mackay (12), Chapman and Putnam (5), Prest (15), Gadd (7), and Karrow (11) indicates agreement on the following points: Under glaciation, the region was depressed by the ice load and, with the retreat of the continental glacier, Lake Frontenac was formed in the Lake Ontario-St. Lawrence Lowlands region. Varved clays were deposited on till during this time. Upon further retreat of the glacier, marine waters invaded the area forming the Champlain Sea. In the Ottawa area these waters reached a level now 690 feet above mean sea-level. In this sea, sedimentation took place, resulting in fine grained sediments in some cases 200 feet thick. Uplift of the land followed but there is some disagreement regarding the exact sequence of events during this uplift.

These marine sediments are extremely sensitive (6) and have been responsible for many landslides along the St. Lawrence River and its tributaries. Considerable effort has been devoted by the National Research Council to the study of the geotechnical properties of these materials.

¹Contribution No. 24, Soil Research Institute, Canada Department of Agriculture, Ottawa, Ont.

²According to Gadd (7, and private communication), "Leda Clay" is a misnomer. The name "Leda" was used to relate the deposits to what was thought to be its most common fossil. It is now known that this is incorrect and that the name "Yoldia" takes precedence (7). The term "clay" is also incorrect because of the silty and sandy nature of some of the materials. Because of the extensive use of the term "Leda Clay" for these materials, it is difficult to establish a more correct name.

In this report, the materials are referred to as marine sediments or Champlain Sea deposits. The name "Rideau Clay" designates the pedological soil profile existing at the surface of some of the marine sediments.

They are the parent materials of a number of agriculturally important soils of which the Rideau is one of the better drained. The morphological and chemical characteristics of the soil profile, as well as its productivity, have been extensively studied and reported in several papers and Soil Survey reports. The present paper deals with the mineralogy of a Rideau Clay soil profile and of selected samples of Champlain Sea sediments.

MATERIALS

Some of the samples of Marine clays and silts were obtained from the Division of Building Research, National Research Council. Their identification in Table 1 is the same as in the paper of Eden and Crawford (6). Two samples of Lake Ojibway-Barlow varved clay from Matheson, Ontario, were obtained from P. A. Rochette, Ecole Polytechnique, Montreal.

The Rideau Clay profile was sampled adjacent to the Central Experimental Farm, Ottawa, on a level bench land area showing no evidence of sheet erosion. The vegetation at the sampling site was grass and wild raspberries and, although the area was not virgin forest land, the site appeared to be free from any major disturbance. The Rideau Clay has a weakly developed profile and lacks distinct pedogenic horizons. Field observation showed that there was an increase in the amount of clay and a gradual change in structure from the surface to the parent material. Although there is no definite evidence that this increase in clay with depth is due to pedogenic processes, the second and third horizons have been designated A₂ and B₁ horizons respectively.

Horizon	Depth (in.)	Colour	Description
A _c	0-9	10YR 3/1	Very dark grey granular clay
A ₂	9-13	5Y 4/2	Olive-grey granular clay
B ₁	13-23	5Y 4/2	Olive-grey, well-developed granular to small blocky clay
C ₁	23-34	5Y 5/2	Olive-grey heavy clay, large blocky structure with fragmental and some conchoidal fractures
C ₂	34-43	5Y 4/2	Olive-grey heavy clay, sub-angular blocky structure with conchoidal fractures
C ₃	43-50	2.5Y 4/2	Dark greyish brown heavy clay, sub-angular blocky structure with conchoidal fractures

METHODS

Mechanical analysis was carried out by segregation of the size separates following H₂O₂ and HCl treatment to destroy the organic matter and carbonates, and dispersion with NaOH. In the case of the Rideau samples, two clay fractions, viz. 2 - 0.2 and < 0.2 micron, were taken, whereas in the case of the Champlain Sea samples a single clay size < 1.4 microns (16-hour sedimentation) was used. The sand fraction was isolated by sieving and the silt fractions by sedimentation.

TABLE 1. — DESCRIPTION OF SAMPLES OF MARINE SEDIMENTS OBTAINED FROM DIVISION OF BUILDING RESEARCH, NATIONAL RESEARCH COUNCIL

N.R.C. No.	Surface elevation	Depth, feet	Description
N.R.C. — Montreal Road			
28- 83	310	6	Fissured oxidized clay
67- 1		11	Stiff grey fissured clay
67- 5		19	Soft grey sensitive clay
67- 8		26	" " " "
67-13		38	" " " "
National Museum			
50-187	235	11	Stiff fissured clay
50-194		26	Firm, highly plastic grey clay
50-197		33	Soft, highly plastic grey clay
50-199		38	" " " "
50-203		48	Very sensitive silty clay "
50-212		67	Grey silty clay
HMCS Gloucester			
65- 7	260	9	Firm, fissured clay
65-13		27	Soft grey sensitive clay
65-18		47	Sensitive silty clay
65-20		55	Soft grey clay
65-22		66	Silty clay
Greens Creek			
64- 9	183	16	Non-calcareous, oxidized, non-saline
64-10	146	23	Calcareous, unoxidized, saline
Nicolet, Quebec			
68- 4	15	13	Sensitive grey clays taken at opposite sides of the crater and near the river following the 1955 Nicolet landslide
68- 6	38	12	

Exchangeable cations, pH and organic matter were determined using the usual techniques of this laboratory (3). Total carbonates, calcite and dolomite were determined using the method of Skinner *et al.* (16).

Mineralogical analysis was carried out using petrographic, staining and X-ray diffraction techniques. The Norelco diffractometer with Fe-filtered Co radiation was used throughout the study.

RESULTS

MECHANICAL ANALYSIS

Table 2a shows the high clay content of the majority of the marine samples. The size distribution of the sample from the National Research Council, from the Museum to a depth of 38 feet, and from Greens Creek is remarkably uniform. On the other hand, samples from greater depth at the Museum, all of the Gloucester samples, and the two from Nicolet show much more variation in size distribution and clay content. The coarser textured samples seem to fall into two categories. In one are those samples, e.g., Museum 48 feet, having a single predominant size, and in the other group there is a somewhat "even" size distribution, e.g., Gloucester 47 feet.

TABLE 2a. — MECHANICAL ANALYSIS OF MARINE SEDIMENTS AS PER CENT OF TOTAL SEPARATES

Depth, feet	>50 micron	50-20 micron	20-5 micron	5-1.4 micron	<1.4 micron
N.R.C. — Montreal Road					
6	1.5	1.4	9.2	23.7	64.2
11	0.3	1.0	9.3	20.1	69.3
19	0.4	1.5	9.5	18.9	69.7
26	0.1	0.7	9.0	16.9	73.3
38	0.0	1.0	9.7	17.2	72.1
Museum					
11	0.2	2.0	15.2	12.9	69.7
26	0.4	3.2	11.3	16.7	68.4
33	2.0	3.1	12.0	15.0	68.0
38	0.3	3.7	15.7	18.3	62.0
48	42.0	16.4	7.8	8.7	25.1
67	2.8	11.1	36.3	16.4	33.5
HMCS Gloucester					
9	1.4	6.8	15.5	14.2	62.2
27	0.2	0.8	8.5	15.5	75.1
47	9.6	13.3	17.9	13.9	45.3
55	1.3	6.1	14.8	17.2	60.6
66	2.9	36.6	34.4	8.3	17.7
Greens Creek					
16	0.0+	0.6	9.7	18.7	70.9
23	0.1	0.7	10.1	20.0	69.0
Nicolet					
13	8.2	27.2	19.7	13.7	31.1
12	3.1	4.3	12.2	18.5	61.9

TABLE 2b. — MECHANICAL ANALYSIS OF RIDEAU CLAY AS PER CENT OF TOTAL SEPARATES

Horizon	Depth, inches	>50 micron	50-20 micron	20-5 micron	5-2 micron	2-0.2 micron	<0.2 micron
A _c	0-9	28.7	7.4	10.8	11.9	28.9	12.3
A _e	9-13	13.7	5.4	8.6	12.3	47.6	12.4
B _t	13-23	8.6	4.3	8.3	11.3	51.7	15.7
C ₁	23-34	1.5	2.8	10.4	14.2	57.5	13.8
C ₂	34-43	12.6	9.3	9.7	10.9	46.6	10.9
C ₃	43-50	8.4	10.1	10.9	12.4	45.7	12.4

In the Rideau Clay profile (Table 2b) there was an increase in clay with a depth to 34 inches and a decrease at the 34-50 inch depth, which may in part be explained by illuviation. However, the fact that the clay content of the lower two horizons is considerably less than in most of the samples of Champlain Sea deposits, and the variation in amounts of the sand and silt fractions among the lower three horizons, both lead to the suggestion that the differences in clay content among the horizons is largely due to the deposition rather than to illuviation. Furthermore, information from soil surveys on the St. Lawrence Lowland shows that soils developed on Cham-

TABLE 3. — CHEMICAL ANALYSES OF RIDEAU CLAY PROFILE. (Expressed on air-dry basis)

Horizon	Depth in inches	pH	Organic matter %	C.E.C. m.e./ 100g.	Per cent saturation			
					Ca	Mg	K	H
A ₂	0-9	5.6	4.1	22.8	69.5	11.9	3.0	15.7
A ₂	9-13	5.9	1.6	30.7	75.2	14.4	2.1	8.3
B ₁	13-23	5.8	1.2	30.0	72.3	16.9	2.5	8.3
C ₁	23-34	5.9	0.8	30.2	65.4	20.4	2.3	11.9
C ₂	34-43	6.0	0.6	27.0	69.7	19.3	2.9	8.2
C ₃	43-50	5.9	0.6	26.8	69.2	19.5	2.7	8.6

TABLE 4. — CALCITE AND DOLOMITE CONTENT OF MARINE CLAY SAMPLES.
(As per cent of air-dry weight)

Depth, feet	Calcite	Dolomite	Total carbonate	Calcite/ dolomite
National Research Council				
6	0.0	0.0	0.0	—
11	0.46	0.14	0.60	3.2
19	0.39	0.12	0.51	3.4
26	0.55	0.16	0.71	3.3
38	0.41	0.34	0.75	1.2
National Museum				
11	0.85	0.0	0.85	—
26	0.89	0.19	1.08	4.7
33	0.70	0.37	1.07	1.9
38	0.97	0.51	1.48	1.9
48	2.74	3.54	6.28	0.8
67	4.00	2.70	6.70	1.4
HMCS Gloucester				
9	4.31	1.42	5.73	3.0
27	0.51	0.58	1.09	0.9
47	3.60	4.10	7.70	0.9
55	3.50	1.99	5.49	1.8
66	6.31	6.20	12.51	1.0
Greens Creek				
16	0.0	0.0	0.0	—
23	0.49	0.17	0.66	2.9
Nicolet				
13	0.93	0.60	1.53	1.6
12	4.62	1.89	6.51	2.4

plain Sea sediments invariably have less clay in the surface horizons than at greater depth.* This would suggest either deposition of coarser material in the last stages of the Champlain Sea, selective removal of fine material by reworking or eluviation following emergence of the sediments from the Sea.

*Stobbe, P. C. *Private communication*

CHEMICAL ANALYSIS

The results of the pH, organic matter, cation exchange capacity and exchangeable cation determinations of the six Rideau soil horizons are shown in Table 3. The most noticeable feature is the lack of any large difference from one layer to another within the profile. The entire profile was slightly acid suggesting a deep leaching subsequent to deposition because all but two of the Champlain Sea materials were calcareous (Table 4). In general, there seems to be a gradual increase in total carbonates with depth. At the N.R.C. and Museum sites, the samples from above 38 feet contained roughly 1 per cent carbonate, whereas those samples taken deeper than 38 feet at the Museum and at HMCS Gloucester contained 5 per cent or more carbonates. However, when these data are compared to the mechanical analysis data, it is evident that the fine textured samples were lower in carbonates than the coarse textured materials. These relationships occurred in spite of the obvious dependence of carbonate content upon the fossil content. If dolomite, only, is considered, the effect of the fossils is eliminated and the dolomite content as well as total carbonate appears to be related to texture.

MINERALOGICAL ANALYSIS

There was no marked difference in mineralogy from one sample to another at a given site or from one site to another. The most notable feature was that quartz, feldspars, amphiboles, micas and chlorites were found in the clay fractions as well as in the silt and sand fractions (Figure 1). The major change accompanying particle size was an increase in phyllosilicates in the small size fractions with a consequent dilution of the other minerals.

Non-clay Fractions

The sands from selected samples of the marine sediments were separated into two specific gravity fractions. Ninety per cent of these sands were < 2.70 sp. gr., and were found by staining techniques to consist of twenty-five per cent quartz, twenty-five per cent plagioclase feldspar and fifty per cent potassium feldspar.

The > 2.70 sp. gr. fractions contained a wider variety of minerals. The predominant heavy minerals were green hornblende and a variety of pyroxenes. The micas consisted mainly of biotite with some muscovite. Appreciable amounts of the chlorite and garnet group minerals were present but could not be distinguished within each group. Staurolite, kyanite, topaz, tourmaline, zircon and titanite were present in more than trace amounts.

One curious, and as yet unexplained, constituent was observed in several of the sand fractions. A considerable portion of the latter consisted of pellets of earthy appearance which could be crushed readily although they obviously had withstood the dispersion techniques used in separation. The pellets were found to be aggregates of minerals, 10 microns and less in diameter, which were shown by X-ray diffraction to be similar mineralo-

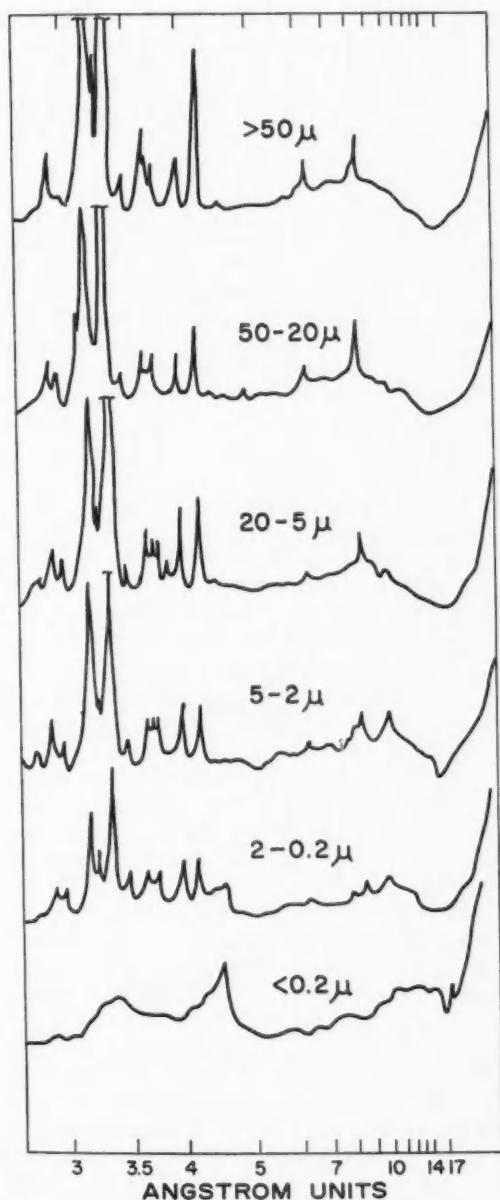


FIGURE 1. X-ray diffraction patterns of randomly oriented powder specimens of the various size fractions of the 43-50 inch sample of the Rideau Clay profile.

gically to the silt fraction. The N.R.C. pellets were light grey to buff in colour whereas the Greens Creek pellets were dark grey to dark brown.

X-ray diffraction patterns of the three silt fractions from all samples showed little variation from sample to sample or from one fraction to another and were in general similar to the patterns of the sand fraction (e.g., Figure 1).

Clay Fractions

Champlain Sea Deposits — Diffraction patterns of oriented specimens of the marine clays showed rather strong mica reflections (e.g., Figure 2), but the N.R.C. and Nicolet samples showed a slightly weaker mica diffraction pattern than the others. The presence of primary minerals, such as quartz, feldspars and amphiboles, caused such a complicated powder pattern that further refinements in the description of the mica were impossible. All samples examined showed very weak reflections at 1.509 and 1.520 Å suggesting dioctahedral characteristics in at least a portion of the phyllosilicates. The sharp weak quartz reflection at 1.53 Å may have masked a possible trioctahedral (060) reflection.

Chlorite was present in some of the samples but no distribution pattern was apparent. Significant amounts were found in the Nicolet sample (68-6) and in all the Gloucester samples except the 47-foot level (65-18). An example of the diffraction pattern of one of these is shown in Figure 2a. In the remainder of the clays, the chlorite diffraction pattern was weak, (e.g., Figure 2b) just detectable, or not detectable.

Expanding layer silicates were shown to occur in all but three samples: viz., 67-5, 50-199 and 64-10, each from a different locality. In general, the expanding material gave a reasonably sharp 14 Å peak in the air-dry state whether it was associated with appreciable amounts of chlorite (Figure 2a) or not (Figure 2b). On glycolation, the material expanded giving either broad 17 Å peaks or 15-17 Å plateaux. Heat treatment resulted in a complete collapse of this material to 10 Å. These are the usual characteristics associated with montmorillonite, although the presence of vermiculite was not excluded on this basis.

Selected samples were segregated into finer sizes in order to determine a possible lower size limit of the feldspars and amphiboles. These minerals were not readily detected with the X-ray diffractometer in either the < 0.2 micron or the < 0.08 micron fractions. However, a long exposure in a powder camera showed definite evidence of them in the fine fractions. Thus, unlike most soils and sediments, the Champlain Sea sediments contain amphibole and feldspar particles less than 0.08 micron in diameter.

Rideau Clay — The Rideau clays were similar to the other marine clays in having appreciable amounts of quartz, feldspars and amphiboles as shown by the different diffractometer patterns of a 2-0.2 micron clay in Figure 3a. Very little chlorite was found in any of the coarse clay fractions and they showed weaker mica patterns than any of the marine clays. The patterns also showed an 11.0 Å peak or shoulder which expanded to 11.8 Å on glycolation and which enhanced the 10 Å peak at 300°C. This may be

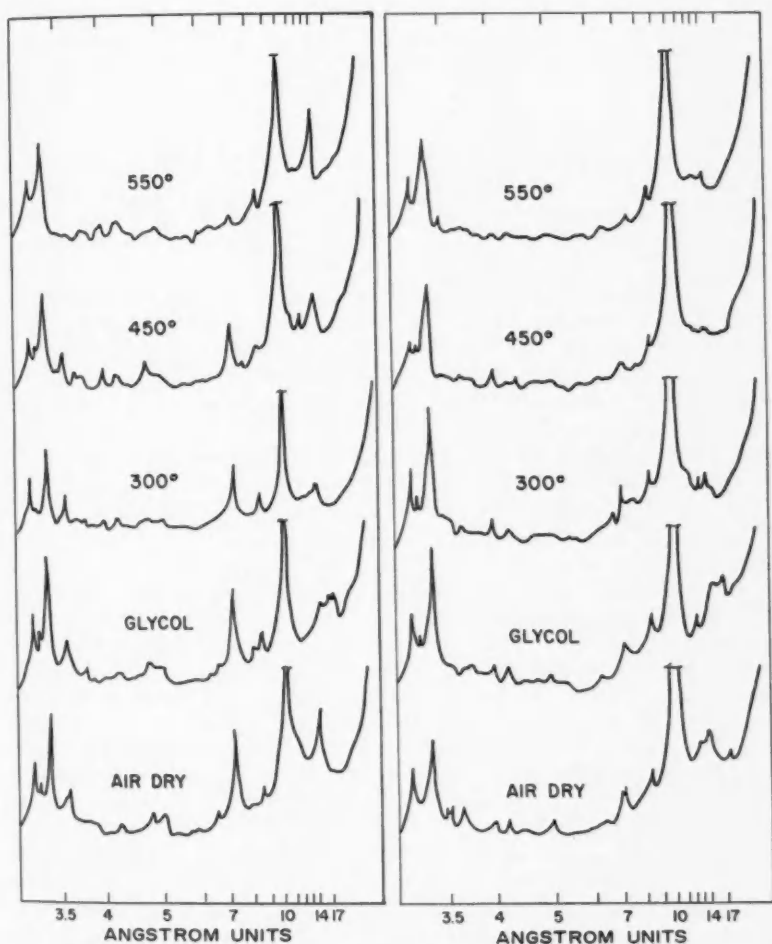


FIGURE 2. X-ray diffraction patterns of oriented specimens of <1.4 microns clay. Figure 2a (left) Gloucester 9 feet. Figure 2b Greens Creek Upper Clay.

interpreted as a random mixed-layer assemblage of 10A mica layers and expanding layers. It was present in all six Rideau horizons in addition to the other minerals noted above.

All six Rideau fine clays gave exceedingly weak diffractometer patterns (e.g., Figure 3b) and powder cameras were used to establish the presence of feldspar and amphibole in this size fraction. Difficulty was found in preparing specimens with a high degree of preferred orientation of the phyllosilicates. The effect of this was that the so-called oriented specimens gave patterns (Figure 3b) similar to those obtained from randomly oriented

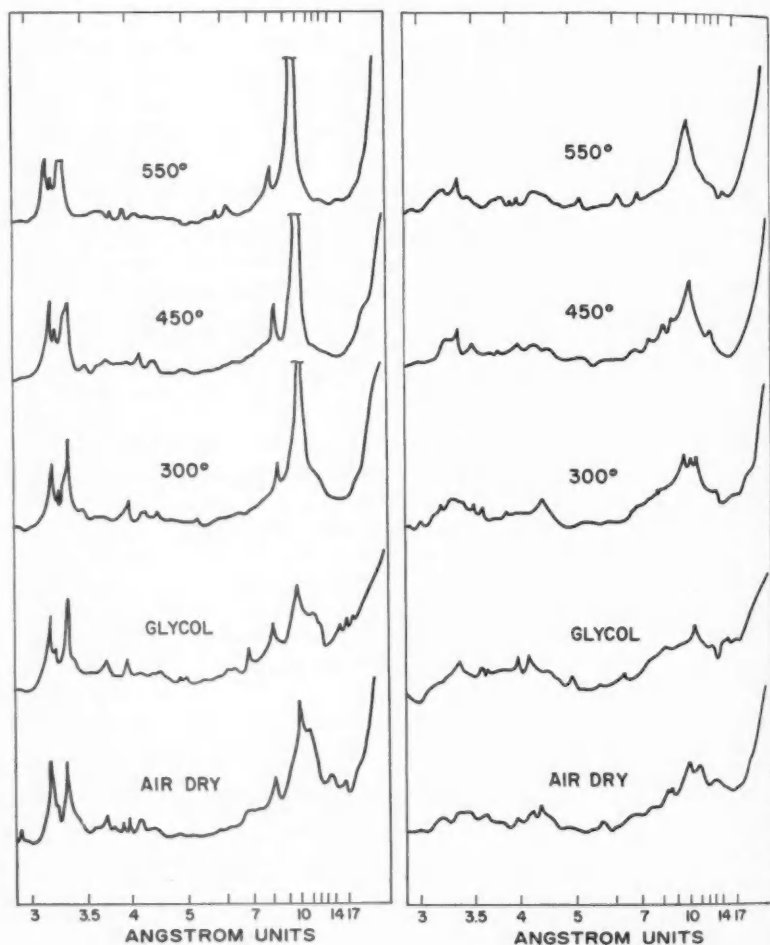


FIGURE 3. X-ray diffraction patterns of oriented specimens of clays from 43-50 inch sample of the Rideau Clay profile. Figure 3a (left) 2-0.2 μ fraction, Figure 3b <0.2 μ fraction.

specimens (Figure 1) which characteristically show the (020) reflection from phyllosilicates at 4.5Å. It may be speculated that the fine size and the large number of minerals combine to cause a weak diffraction pattern of each mineral and that the unusually large percentage of non-platy minerals prevented the platy minerals from forming a uniform flat surface. However, there was sufficient regularity to show that montmorillonitic material and interstratified mica-hydrated layer material of indefinite nature was present in addition to the quartz, feldspars and amphiboles.

Varved Clays — The Matheson varved clays were also similar to the marine sediments in having quartz, feldspars, amphiboles, micas and chlorites in the clay fractions. Their special feature was a 17A montmorillonite of higher intensity than the marine clay.

DISCUSSION

The variation in the texture of the Champlain Sea sediments may be attributed to depositional differences. The rather uniform fine-textured materials in the upper part of the sections studied suggests a quieter depositional environment during the later stages of sedimentation than during the earlier.

Generally, from a qualitative point of view, the results of the mineralogical analysis obtained in the present investigation agree reasonably well with those published previously (1, 4, 10, 13, 14). In the early work carried out by differential thermal analysis (DTA), samples of marine clays were found to consist of quartz, mica, and montmorillonite. In later investigations (1, 4, 10) using other methods, additional minerals were found which either gave no thermal reactions or were not present in sufficient quantity to be detected. It may be concluded, therefore, that the earlier work generally does not disagree with later results but that the results were incomplete.

Beland (4), without giving his methods of analysis, stated that the marine clay material was mostly feldspar and quartz, and that there was a "subordinate amount of mica fragments and a very small quantity of clay minerals, commonly montmorillonite and kaolinite". Karrow (10) found chlorite, illite, amphibole, quartz, feldspar and, sometimes, calcite. In addition, he stated that quartz accounted for 10 per cent or less of the material and that feldspar was of the same order of magnitude. In three Quaternary marine clay samples, one from near Ottawa and two from south of Montreal, Allen and Johns (1) found hydrous mica, chlorite, vermiculite, montmorillonite, mica-chlorite mixed layer, quartz, feldspar and amphibole. It is considered that these differences in the mineralogy of the clay fraction might be resolved by consideration of the method of analysis or ease of interpretation.

Feldspar was thought to be a major component (4), minor to trace (1), and about 10 per cent (10). In the present investigation, the major portion of the sand was found, by optical means, to be potassium and plagioclase feldspars. Feldspars have perfect (001) cleavage, and it might be suggested that the coarser material lends itself better to preferred orientation than the finer material. Consequently, the (002) diffraction peak would be more intense in the coarse than in fine material. The possibility is also considered that the (hkl) reflections would either increase slightly in intensity or would not change in going from coarse to fine particle size. In actual fact, the (002) reflection at 3.2A decreased in intensity with particle size whereas the (hkl) reflections between 3.5 and 4.0A maintained a rather uniform value (Figure 1). Since no attempt has been made to deal in absolute values, and since the degree of preferred orientation is unknown, no quantitative value can be assigned to the feldspars. However, since the

(hkl) reflections remained rather uniform, we can conclude with confidence that there is a significant amount of feldspars in the clay fraction.

Amphiboles were identified by Karrow (10), Allen and Johns (1), and in the present investigation, but not by Beland (4).

Mica, hydrous mica, or illite was found by all workers and, in fact, all but Beland (4) reported this group to predominate. The evidence in the present investigation suggests that mica is the predominant *clay mineral* but not necessarily more abundant than the feldspars in the clay fraction.

Kaolinite was reported by Beland (4) but, since it was not corroborated by the other workers, the possibility must be recognized that a chlorite second order reflection from X-ray diffraction may have been interpreted as kaolinite.

Chlorite was found in all samples by Karrow (10) and in a single sample by Allen and Johns (1). In the present work, chlorite was present in some cases and not in others and, since no relationships were apparent, more work will have to be done in order to determine the reasons for the variation in chlorite content.

The hydrated-layer clay minerals montmorillonite, vermiculite, and mixed-layer minerals were reported in a number of cases (1, 4, 10, 14), and were found in all but three samples of the present investigation.

From the mineralogical analyses of the numerous samples from widely separated sites which are reported here and in the literature, some generalizations can be made. Quartz, feldspars, amphiboles and micas occur in the clay fraction of all samples although the variation in the amounts is unknown. Chlorite, vermiculite, montmorillonite and mixed-layer minerals were found in some but not all samples from each location.

The origin of the chlorite, vermiculite, montmorillonite and mixed-layer minerals is unknown. They may all have been inherited and have remained unchanged, or they may have been formed *in situ*. Karrow (10) has suggested that chloritization has taken place in the marine environment. It is also possible that montmorillonite, vermiculite and mixed-layer minerals have been formed by the removal of inter-layer K or Mg in mica or chlorite respectively. There is no concrete evidence favouring any of these alternatives.

Amphiboles are generally considered to be easily weatherable, and are rarely found in the < 0.2 micron clay fraction of the usual soils and sediments. Since they were found in the < 0.08 micron fraction of the marine sediments, it is inferred that chemical alteration of the silicates was not appreciable. The presence of calcite except in the surface materials also suggests the lack of drastic weathering.

The Rideau Clay profile differed somewhat from the deeper Champlain Sea sediments from which it was derived. Carbonates were absent and the pH was slightly acid in the entire profile. Greater amounts of hydrated-layer clay minerals appeared to be present than in the deeper sediments. There was also an interstratified mica-hydrated mineral assemblage which was present as a unique constituent of the Rideau profile. The various

horizons could not be distinguished on the basis of mineralogy and the exchange chemistry was remarkably uniform throughout the profile. The lack of uniformity in amounts of the silt and sand fractions of the different horizons suggested that the increase in clay down to a depth of 34 inches was due largely to depositional differences rather than to illuviation.

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THE EFFECT OF FREEZING-THAWING AND WETTING- DRYING CYCLES ON SOIL AGGREGATION¹

MIKKO SILLANPÄÄ² AND L. R. WEBBER³
Ontario Agricultural College, Guelph, Ontario

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ABSTRACT

Three fractions: 1) natural aggregates 2 to 3 mm.; 2) aggregates <0.25 mm. prepared by crushing 2- to 3-mm. aggregates; and 3) aggregates <0.25 mm. obtained by sieving the dry soil, were acquired from the Waupoos silty clay loam. After five cycles of wetting and drying, and freezing and thawing, the mean weight-diameter (M.W.D.) was determined after wet-sieving. Cycles of wetting and drying increased the M.W.D. of the large aggregates but did not cause significant changes in the fractions <0.25 mm.

Cycles of freezing and thawing at moisture contents near saturation significantly decreased the M.W.D. of the large aggregates and increased the M.W.D. of the crushed aggregates at both rates of freezing. A significant decrease occurred in the M.W.D. of the original aggregates <0.25 mm. at the slower rate of freezing.

INTRODUCTION

The beneficial influence of wetting and drying, and freezing and thawing, on the water-stability of soil aggregates is accepted by some investigators and doubted by others. McHenry and Russel (8) reported that 20 cycles of wetting and drying increased the percentage of aggregates > 0.25 millimetre in a bentonite-sand mixture and that after a maximum value was reached a decrease occurred. Other studies (18) have shown a decrease in aggregation with alternate wetting and drying. A partial explanation for the differences in the results may lie in the method of wetting a sample prior to wet sieving. It has been reported that as the rate of wetting is increased there is an increase in the breakdown of the aggregates (9, 13, 14).

Gardner (4) has shown that freezing assisted in the restoration of soil structure that had been damaged by sodium salts, provided the sodium had been replaced, in part, by calcium. Baver (1) stated that cycles of freezing and thawing cause a granulating action in soils and that organic matter was a prerequisite to the formation of stable aggregates. Czeratzki (3) observed beneficial results from the action of frost on ploughed clay soils. He also reported that the aggregates formed during the winter and a crumb structure from the preceding autumn were destroyed by spring thawing when the soil moisture was high.

Slater and Hopp (16) and Willis (18) were able to demonstrate the disintegration of soil aggregates by alternate freezing and thawing. The greatest breakdown occurred at the highest soil moisture contents. Similar results were obtained by Logsdail and Webber (7) when they used a soil at a high level of aggregation, but they were unable to obtain significant changes, expressed as the geometric mean, on a soil at a low level of aggregation. Chepil (2) recognized a two-directional effect from freezing

¹Report on research conducted at the Department of Soil Science, Ontario Agricultural College, Guelph, Ont., while the senior author was the recipient of a National Research Council Post-Doctorate Fellowship, 1959-1960.

²Professor of Soil Science, Helsinki, Finland.

³Associate Professor of Soils, Ontario Agricultural College, Guelph, Ont.

and thawing on soil aggregation. He reported that a decrease in the percentage of the large water-stable aggregates was accompanied by a decrease in the percentage of the fine aggregate fraction.

Numerous freezing and thawing, and wetting and drying experiments have been conducted on soils with a wide range in the size of the aggregates. The results, in most cases, indicate a lower level of aggregation after the trials, especially at the higher moisture contents. The study reported herewith was undertaken to measure the changes in aggregation when aggregates within narrow size limits were frozen and thawed, or wetted and dried through several cycles.

MATERIALS AND METHODS

A surface sample of the Waupoos silty clay loam, a Grey Brown Podzolic soil, was air-dried and dry-sieved to obtain three aggregate fractions:

- (a) Original aggregates, 2.0 to 3.0 millimetres in diameter.
- (b) A mixture of aggregates, 0.25 to 0.10 millimetre and < 0.10 millimetre in diameter and mixed in a 1:1 ratio. These fractions were obtained by crushing aggregates 2.0 to 3.0 millimetres in size.
- (c) Original aggregates 0.25 to 0.10 millimetre and < 0.10 millimetre mixed in a 1:1 ratio, obtained by dry sieving.

Fifty grams of air-dried aggregates were placed in an aluminum cylinder, 2 by 2 inches, fitted with a fibreglass base. Four moisture levels were established: (i) air dry; (ii) near saturation, 56.7 per cent — the moisture retained by the soil that had been saturated and allowed to drain freely for 30 minutes; (iii) $\frac{1}{2}$ -atmosphere percentage, 41.5 per cent as determined on a porous plate (12); and (iv) 15-atmosphere percentage, 18.9 per cent by the pressure membrane method (11). These moisture contents were attained by wetting the samples and then permitting evaporation from the exposed ends. When the desired weight was reached, the cylinder containing the soil was enclosed in a polyethylene bag. The samples were allowed to stand for 2 days to obtain an equal moisture distribution.

The following treatments of wetting, drying, freezing, and thawing were carried out:

- a. Check, using air-dried samples.
- b. Wetting to near-saturation and drying to air-dry condition (5 cycles).
- c. Wetting to near saturation and drying to 15-atmosphere percentage and then 5 cycles of slow freezing at -3°C . and thawing at 22°C .
- d. Same as c., but dried to $\frac{1}{2}$ -atmosphere percentage.
- e. Wetting to saturation and 5 cycles of slow freezing at -3°C . and thawing at 22°C .
- f. Same as c., but fast frozen at -25°C .
- g. Same as c., but dried to $\frac{1}{2}$ -atmosphere percentage and fast frozen at -25°C .
- b. Same as e., but fast frozen at -25°C .

Two rates of freezing were achieved by placing the samples in controlled-temperature cabinets held at $-3 \pm 0.5^\circ\text{C}$. and $-25 \pm 1.0^\circ\text{C}$. Thermocouples, imbedded in extra samples and connected to a multipoint recorder, were used to record the time required for a sample to cool from 22°C . to the temperature of the cabinet. The samples were held at the temperature of the cabinet for 4 to 6 hours. Samples were allowed to thaw at 22°C . in the sealed polyethylene bags with no apparent change in the moisture content of the sample.

The samples were prepared for aggregate size analysis by allowing the soil to air-dry in the cylinder, then wetted with distilled water entering at the base of the cylinder by capillary action along a ribbon of cloth 1 inch in width (15). The wet soil was transferred to a wet-sieving apparatus and the procedure of Logsdail and Webber was followed (7). The mean weight-diameter (M.W.D.) of the aggregates was calculated according to the method proposed by Youker and McGuinness (19).

The organic matter content of the samples was determined according to the method proposed by Peech *et al.* (10). The exchange capacity was determined by the method described by Jackson (5). The particle-size distribution of the fractions was determined using the method proposed by Kilmer and Alexander (6).

The mean weight-diameter of the aggregates for any treatment is the average of three replicates. The necessary difference for significance at the 5 per cent level, between extreme treatments in the array, was calculated and used for all comparisons (17).

RESULTS AND DISCUSSION

The principal physical and chemical properties which are believed to affect the aggregation of the three aggregate fractions are given in Table 1. The percentage of clay and organic matter are lower in the original aggregates < 0.25 millimetre than in the other two fractions. The lower cation exchange capacity is a result of less clay and organic matter.

Original Aggregates, 2 to 3 millimetres

The mean weight-diameter (M.W.D.) of the air-dried aggregates should be 2.5 millimetres assuming a normal distribution between these size limits. The wet-sieving procedure on the check treatment reduced the

TABLE 1. — THE PER CENT CLAY, SILT, AND ORGANIC MATTER AND CATION EXCHANGE CAPACITY (C.E.C.) OF THE THREE AGGREGATE FRACTIONS

Aggregate fraction	Clay <2 _a per cent	Silt 2 to 20 _a per cent	Organic matter, per cent	C.E.C. m.e./100 gm.
A. Original, 2-3 mm.	36.3	51.9	6.2	28.5
B. Crushed, <0.25 mm.	35.6	50.5	6.3	29.2
C. Original, <0.25 mm.	29.3	50.7	5.4	24.7

M.W.D. to 1.45 ± 0.13 millimetres, which will be considered as a basis for comparing the effects of other treatments (Table 2). The five cycles of wetting to saturation and then air-drying, treatment *b*, resulted in aggregates with a M.W.D. of 1.92 ± 0.07 millimetres, which was a significant increase over the check (Table 2).

Slow or fast freezing at the 15-atmosphere percentage, treatments *c*. or *f*., was similar in effect to the dehydration cycles, in that aggregation was significantly increased over the check but was no different than treatment *b*. However, as the moisture content at the time of freezing was increased there was a significant decrease in the M.W.D. of the aggregates.

It has been established (1) that slow freezing results in a relatively small number of large ice crystals that form in tension-free pore spaces. The crystals increase in size by drawing water from soil pores. If the soil is cooled at a faster rate, the ice crystals increase in number but remain relatively small in size (1). The results in Table 2 indicate that more disruptions of aggregates occurred at -25°C . than at -3°C ., treatments *d*, *e*, *g* and *h*. The dehydration as a result of freezing was not effective in stabilizing the aggregates against wet-sieving.

Crushed Aggregates, <0.25 millimetre

Five cycles of wetting and drying, treatment *b*, and the slow freezing at 15 and $\frac{1}{2}$ -atmosphere percentages, treatments *c* and *d*, did not result in significant increases in the M.W.D. of the aggregates over the check treatment. The increases obtained by fast freezing at 15 and $\frac{1}{2}$ -atmosphere percentages were significant. However, both rates of freezing at the near-saturation moisture content, treatments *e* and *h*, resulted in M.W.D. values

TABLE 2.—MEAN WEIGHT-DIAMETERS OF THREE AGGREGATE FRACTIONS FROM WAUPOOS SILTY CLAY LOAM AFTER VARIOUS TREATMENTS AND WET SIEVING

Treatment	Mean weight-diameter in millimetres		
	Original 2 to 3 mm.	Crushed to <0.25 mm.	Original <0.25 mm.
a. Check, air-dried aggregates	1.45	0.13	0.15
b. Wet to sat. to air-dry, 5 cycles	1.92	0.20	0.14
<i>Slow freeze at -3°C.; thawed at 22°C.; 5 cycles</i>			
c. Wet to sat., dry to 15 atm.	2.09	0.17	0.13
d. Wet to sat., dry to 1/3 atm.	1.56	0.21	0.15
e. Wet to sat.	1.01	0.44	0.20
<i>Fast freeze at -25°C.; thawed at 22°C.; 5 cycles</i>			
f. Wet to sat., dry to 15 atm.	2.12	0.24	0.14
g. Wet to sat., dry to 1/3 atm.	1.40	0.23	0.15
h. Wet to sat.	0.62	0.32	0.15
Necessary difference ($P = 0.05$)	0.32	0.09	0.04

that were significantly greater than the check (Table 2), a result that was opposite to that obtained with the original 2- to 3-millimetre aggregates.

In discussing the effects of slow and fast freezing on aggregation, Bayer (1) noted that a quick freeze ($-190^{\circ}\text{C}.$) at high moisture contents resulted in better aggregation than when the freezing occurred at $-10^{\circ}\text{C}.$ To account for the increase in the M.W.D. of the crushed aggregates, it is postulated that the slow freezing at $-3^{\circ}\text{C}.$ drew the water out of soil pores under tension to freeze as large crystals in tension-free pore spaces. The combined influences of pressure from crystal growth and the dehydration produced stable aggregates. When the wet soil was cooled quickly to $-25^{\circ}\text{C}.$ the water froze *in situ* with the result that the expansion brought the particles in firm contact with one another. The stability of the aggregates would be enhanced by the cycles of freezing and thawing, and the presence of clay and organic matter (Table 1).

Original Aggregates, <0.25 millimetre

Apparently none of the treatments caused significant differences in the M.W.D. of the aggregates when compared with the check, except for the slow freeze at saturation, which gave a M.W.D. value of 0.20 ± 0.04 millimetre (Table 2). It is suggested that the failure to achieve significant increases in stable aggregation was due to the lower contents of clay and organic matter in this aggregate fraction (Table 1).

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SUITABILITY FOR IRRIGATION OF A SOLONETZIC SOIL COMPLEX IN EAST-CENTRAL ALBERTA¹

K. K. KROGMAN AND R. A. MILNE

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ABSTRACT

Soil samples were taken from the surface 6 inches, the 6- to 12-inch depth, and thereafter by 1 foot increments down to the 15-foot depth in Hemaruka (Brown Solodized-solonetz) and Halladay (Brown Solod) soils that had been used in an irrigated plot study. Analyses of the samples showed that the Hemaruka soil is a saline-alkali soil, the undesirable characteristics of which were aggravated by 6 years of irrigation. Yields of wheat, oats, and barley obtained in the plot study indicated the inferior productivity of the Hemaruka soil as compared with the Halladay soil. The Halladay soil is non-saline and non-alkali within the solum but has a dense saline-alkali subsoil similar to that of the Hemaruka soil. Inadequate internal drainage, as indicated by low disturbed hydraulic conductivity values, would make this soil complex unsuitable for irrigation.

INTRODUCTION

A belt of Solonetzic soils, forming a complex of Solodized-solonetz and Solod intergrades (2), covers about 7,000,000 acres in that part of Alberta lying south of Edmonton and east of the fifth meridian (3). This belt includes parts of the Black, Shallow Black, Dark Brown, and Brown soil zones. A considerable portion of the land presently irrigated or proposed for irrigation is included in this belt.

Marshall and Palmer (1) and Palmer² reported that, in the Tilley area east of Brooks, Alberta, irrigation farming on Solonetzic soils has been practised without serious soil deterioration through accumulations of alkali salts. However, the underlying geological formation in the Tilley area is primarily of fresh water deposition (7). The main geological formation associated with the Solonetzic soils in the proposed Red Deer River Diversion Irrigation Project is a marine shale, high in alkali (sodium) content (6). Such formations may contribute toxic quantities of salts to soils when they are placed under irrigation (5). Thus, the Solonetzic soils in the proposed irrigation project may be unsuitable for irrigation.

Irrigated plot tests were conducted from 1952 to 1957, inclusive, to determine the consumptive use of water for the growing season in the region of the proposed irrigation project. They showed large variations in crop yield, which were more closely associated with soil variations than with amounts of irrigation water applied.³ Therefore, some physical and chemical properties of these soils were studied to explain the yield variations and to assess the suitability of the soils for large-scale irrigation development.

MATERIALS AND METHODS

Samples of the solum and of the underlying material of two Solonetzic soil series in east-central Alberta were taken in the fall of 1957. These soils belong to the Hemaruka and Halladay series, which are Brown Solodized-

¹Joint contribution from the Soils Section, Canada Agriculture Research Station, Lethbridge, Alta., and the P.F.R.A. Drainage Division, Vauxhall, Alta.

²Palmer, A. E. Change in amounts and position of water soluble salts in the top 6 feet of soil during 35 years of irrigation farming in the Tilley and Brooks areas of the Eastern Irrigation District, Alta. Dom. Experimental Station, Lethbridge, Alta. 1951. *Unpublished*.

³*Unpublished data*. Annual reports, Experimental Farm, Lethbridge, Alta. 1952-1957.

TABLE 2. — ELECTRICAL CONDUCTIVITIES OF THE SATURATION EXTRACTS, SODIUM ADSORPTION RATIOS, AND DISTURBED HYDRAULIC CONDUCTIVITIES OF NON-IRRIGATED AND IRRIGATED HEMARUKA AND IRRIGATED HALLADAY SOILS

Depth (feet)	EC _s x 10 ³						SAR						HC (inches per hour)					
	Non-irrigated Hemaruka		Irrigated Hemaruka		Irrigated Halladay		Non-irrigated Hemaruka		Irrigated Hemaruka		Irrigated Halladay		Non-irrigated Hemaruka		Irrigated Hemaruka		Irrigated Halladay	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
0-0.5	0.6	0.1	4.7	2.6	1.1	0.2	4.0	0.7	18.6	3.6	2.0	0.3	3.40	0.81	0.60	0.15	1.80	0.68
0.5-1	1.6	1.0	5.6	1.7	0.6	0.1	9.0	1.2	20.8	2.6	0.5	0.1	0.05	0.04	0.36	0.30	1.33	0.48
1-2	4.1	1.7	10.8	1.4	1.4	0.2	15.8	4.9	22.3	2.1	1.0	0.1	0.16	0.09	0.04	0.01	0.56	0.12
2-3	7.2	2.8	11.7	1.7	2.5	1.5	16.7	3.7	23.1	2.1	8.0	3.0	0.22	0.14	0.06	0.05	0.32	0.14
3-4	7.0	1.2	9.7	0.2	1.4	0.8	20.9	2.6	22.1	1.5	3.0	1.5	0.05	0.04	0.01	0.00	0.11	0.06
4-5	9.7	0.9	10.2	0.5	3.4	2.2	19.8	1.3	21.9	0.6	13.5	6.0	0.13	0.06	0.03	0.00	0.19	0.09
5-6	8.7	0.6	8.2	0.8	5.0	1.9	19.8	1.6	18.2	1.1	10.2	4.7	0.18	0.10	0.06	0.02	0.11	0.06
6-15	7.6		6.4		5.4		19.8		15.3		16.9		0.04		0.06		0.08	

solonetz and Brown Solod soils, respectively. A generalized description of the Hemaruka and Halladay soils, as given by Alberta Soil Survey, is as follows:

Hemaruka loam — Brown Solodized-solonetz:

A ₁	0 to 6 inches	Light brown loam, weakly platy
A ₂	1 to 1½ inches	Light grey brown loam to silt loam, platy crushing to a loose powder
B ₂	5 to 10 inches	Very dark brown clay, columnar with round tops
B _{2a}	4 to 8 inches	Low to medium line accumulation
C		Heavy-textured till containing traces of coal and shale fragments

Halladay loam — Brown Solod:

A ₁	6 to 10 inches	Brown loam, moderately platy
A ₂	0 to 3 inches	Grey brown, platy
B ₂	4 to 8 inches	Weakly columnar with flat tops
B _{2a}	4 to 8 inches	Massive to fragmental clay loam, line flecks
C		Clay loam to clay till

The samples were taken from or near plots located 10 miles southwest of Youngstown, Alberta. These plots had been cropped and irrigated during the previous 6 years. Each plot was 0.05 acre in size, and both soils were represented in varying amounts on most of the plots. The plots from which the soil samples were taken had been irrigated each year with about 8 inches of water applied in four to five irrigations.

Samples of soil were taken at four locations on irrigated Halladay loam, four locations on irrigated Hemaruka loam, and four locations on non-irrigated Hemaruka loam within 100 feet of the plot area. The samples were obtained from the surface 6 inches, the 6- to 12-inch depth, and thereafter by 1-foot increments down to the 15-foot depth at each of the 12 locations. Sampling was done by depth increments rather than by horizons because the soil on the plots had been intensively cultivated to the 6- to 8-inch depth. At the non-irrigated Hemaruka sampling sites the surface 6-inch samples corresponded approximately to the A horizon; the 6- to 12-inch samples included most of the B₂ horizon; and the 1- to 2-foot samples included the B_{2a} horizon.

The samples were used for the determination of saturation percentage, pH of the saturation paste, electrical conductivity of the saturation extract, soluble Na, Ca, and Mg, and disturbed hydraulic conductivity. With some minor modifications the methods used in the analyses were those outlined in U.S.D.A. Handbook 60 (4).

The irrigation water used in the plot study was obtained from a nearby stock-watering dam. The salt content of this water was 234 p.p.m. with a sodium adsorption ratio of 1.6. This is considered to be good quality irrigation water. Thus, any changes in the chemical nature of the soil are thought to be due to movement of salts in the soil and not to salts contained in the irrigation water.

RESULTS AND DISCUSSION

The saturation percentages for both soils increased with depth to a maximum at 3 feet in the Hemaruka soil and at 6 feet in the Halladay soil, as shown in Table 1. This increase in saturation percentage with increasing

depth is a reflection of the change in texture and indicates the heavy texture of the parent materials. The data show that the saturation percentages in the upper 2 feet of the Hemaruka soil were considerably higher where this soil was cultivated and irrigated than where it was in the native state. This could have been partly caused by the mixing of the A and B horizons through plot preparation and cultivation. Furthermore, the relatively higher sodium content of the irrigated Hemaruka soil would tend to result in higher saturation percentages. On the basis of hand texturing, the soils varied from fine sandy loam to clay loam in the upper 3 feet, with clay loam in the 3- to 15-foot depths. The surface 6 inches of the non-irrigated Hemaruka soil varied from fine sandy loam to loam, and of the irrigated Hemaruka soil from loam to clay loam.

The pH of both soils was near neutrality for the samples taken from the surface 6 inches and increased with depth to maximal values in the 2- to 3-foot depth (Table 1). Below 6 feet the soil was slightly and uniformly alkaline. In the upper 2 feet the pH of the irrigated Hemaruka soil was higher than that of the non-irrigated Hemaruka soil, indicating that the alkalinity of this soil had increased as a result of irrigation.

The electrical conductivities of the saturation extracts (EC_e), the sodium adsorption ratios (SAR), defined as $Na/\sqrt{\frac{Ca + Mg}{2}}$, and the dis-

turbed hydraulic conductivities (HC) are given in Table 2. Except for the top foot of the non-irrigated Hemaruka soil, the EC_e values were considerably greater than 4 mmhos./cm. at all depths in both the irrigated and the non-irrigated Hemaruka soil. The EC_e values for the Halladay soil were less than 4 mmhos./cm. in the upper 6 feet of the profile but below this depth were greater than 4 mmhos./cm. and were similar to those of the Hemaruka soil at depths below 10 feet. The EC_e values for the top 5 feet of the irrigated Hemaruka soil were greater than those of the non-irrigated Hemaruka soil, but below this depth they tended to be less than those of the non-irrigated soil. This suggests that irrigation of the Hemaruka soil had caused an upward movement of salts in the profile.

The total soluble salt content of the non-irrigated and the irrigated Hemaruka soil was calculated using the EC_e and saturation percentage data. In the non-irrigated Hemaruka soil the total soluble salts amounted to 22.15 tons per acre in the top 5 feet and 58.40 tons per acre in the 5- to 15-foot depth. In the irrigated Hemaruka soil the total soluble salts amounted to 40.41 tons per acre in the top 5 feet and 50.09 tons per acre in the 5- to 15-foot depth. Although the apparent increase in soluble salts in the top 5 feet was greater than the decrease in the 5- to 15-foot depth, part of the increase may have been due to the salts added by the irrigation water. Salts added by the irrigation water, calculated on the basis of 234 p.p.m. soluble salt, would be about 1.33 tons per acre.

The SAR values down to the 6-foot depth were much higher for the Hemaruka soil than for the Halladay soil. The values for the upper 5 feet of the Hemaruka soil were higher where this soil was irrigated than where it was not irrigated. In the surface foot this was due to an increase in

sodium content as well as a decrease in calcium and magnesium content, and in the 1- to 5-foot depth it was due mainly to an increase in soluble sodium.

Soils with exchangeable sodium percentages greater than 15, EC_e values over 4 mmhos./cm., and pH values less than 8.5 are classed as saline-alkali soils (4). Such soils may become impermeable to water when irrigated and are, therefore, of limited value for irrigation (4, 5). In addition, the excess salts increase the osmotic pressure of the soil solution and thus hinder water uptake by plants. Using the conversion factor given in Reference 4, page 26, the SAR value corresponding to an exchangeable sodium percentage of 15 would be 13.8. Therefore, except for the surface foot, the non-irrigated Hemaruka soil would be a saline-alkali soil for the entire depth sampled. Where the Hemaruka soil was cultivated and irrigated, all depths, including the top foot, were saline-alkali. The irrigated Halladay soil was non-saline and non-alkali in the top 4 feet, but below this depth it was saline-alkali soil similar to the Hemaruka soil.

Adequate internal drainage is of primary importance in irrigated soils, especially where excess salts must be removed from the root zone. Hydraulic conductivities as low as 0.04 inch per hour are considered to indicate the lower limit of suitable permeability for irrigation and leaching (4). The HC values for the two soils showed that relatively impervious horizons are present within 15 feet of the surface in both soils although the depth at which they occur is lower in the Halladay than in the Hemaruka soil. The values for the upper 3 feet of the Halladay soil were greater than 0.30 inch per hour, whereas at all depths except the top foot of the Hemaruka soil they were less than about 0.20 inch per hour. The HC values for the upper 8 feet of the irrigated Hemaruka soil were less than those of the non-irrigated Hemaruka soil. Below the 8-foot depth the HC values for both soils were less than 0.10 inch per hour. At the 9-foot depth of the non-irrigated Hemaruka soil the values averaged 0.03 inch per hour and at the 15-foot depth averaged 0.01 inch per hour. In the irrigated Hemaruka soil the minimum HC value occurred at the 3-foot depth where it averaged 0.01 inch per hour. The minimum HC value for the irrigated Halladay soil occurred at the 15-foot depth where it averaged 0.04 inch per hour.

The correlation coefficients showing the relationship between the HC and EC_e values and between the HC and SAR values were negative and highly significant ($r = -0.54$ and -0.60 , respectively). Thus, where the EC_e and SAR values were large, the HC values tended to be small. Also, the correlation between the HC values and the saturation percentages was negative and highly significant ($r = -0.64$), indicating that low HC values were associated with the heavier soil textures.

In 1955 and 1956, yield data paired on the basis of soil type were obtained for wheat, oats, and barley from plots where the Hemaruka and Halladay soils occurred within the same plot. The average yields of each crop in each year for the two soils were calculated, irrespective of plot

TABLE 3.—MEAN YIELDS OF CEREAL CROPS GROWN ON HEMARUKA AND HALLADAY SOILS, AND SIGNIFICANCE OF DIFFERENCES BETWEEN MEANS

Year	Crop	Yield (bu./acre)				Significance of difference	
		Hemaruka		Halladay			
		Av.	± S.D.	Av.	± S.D.	D.F.	t value
1955	Wheat	21.8	8.5	50.1	11.6	32	15.72**
	Oats	47.0	17.2	84.4	13.4	16	9.50**
	Barley	19.4	6.3	45.2	11.4	17	10.32**
1956	Wheat	28.4	11.7	46.0	14.3	52	2.53*
	Oats	72.2	21.5	109.6	17.5	39	9.84**
	Barley	43.3	13.0	73.4	11.5	14	7.92**

*Significant at 5% level

**Significant at 1% level

treatment. These averages, together with the standard deviations and differences as indicated by the "t" test, are given in Table 3.

The average yields of cereals grown on the Halladay soil were about one and one-half to two times as large as those grown on the Hemaruka soil. Except for wheat in 1956, when the difference in yield between the two soils was significant at the 5 per cent level, the differences between yields obtained from the two soils were all significant at the 1 per cent level. The standard deviations indicated considerable variation in yields for any one crop year within each soil type. However, this variation was due to the influence of plot treatment including different amounts of irrigation water applied as well as to variations within each soil series.

CONCLUSIONS

The soluble salt content (particularly sodium) indicated that the Hemaruka soil is inferior to the Halladay soil. Although yields of crops grown on the irrigated Halladay soil were satisfactory and much higher than those of crops grown on the irrigated Hemaruka soil, the two soils occur in such close association that it would be impossible to separate them on a farm field basis. Also, the internal drainage at lower depths in both soils is low, as indicated by low HC values. Thus, reclamation measures involving leaching would be unsuccessful, and continued irrigation would result in still greater accumulation of salts near the surface. Therefore, on the basis of these studies the Hemaruka-Halladay soils complex of east-central Alberta should be considered unsuitable for irrigation unless the internal drainage characteristics can be greatly improved.

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POTASSIUM-SUPPLYING POWER OF SOME CANADIAN SOILS¹

A. J. MACLEAN

Canada Department of Agriculture, Ottawa, Ontario

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ABSTRACT

The amounts of exchangeable potassium in surface samples of 11 Canadian soils were significantly correlated with uptake of potassium by plants in the greenhouse. Per cent K-saturation and water-soluble potassium were indicative of the percentage of K-uptake that was derived from soil potassium in exchangeable form at the time of seeding.

Amounts of non-exchangeable potassium extracted from the soils by repeated boiling in 1 N HNO_3 , by H-saturated exchange resin, and by continuous leaching with 0.01 N HCl were significantly correlated with each other and with the amounts of this form of potassium removed by plants.

Following cropping, release of non-exchangeable potassium to exchangeable form during moist incubation of the samples for 112 days was slight. When samples containing different levels of exchangeable potassium were incubated moist for 13 months and then wetted and dried five times, potassium tended to be released to exchangeable form or converted to non-exchangeable form depending on initial level established. The degree of K-saturation at which potassium in six Ontario soils would be expected to be at equilibrium was estimated by regression to be 1.21 per cent. There was evidence that the degree of K-saturation for equilibrium in a Brown soil from Saskatchewan was at least 4.5 per cent.

INTRODUCTION

The capacity of soils to supply potassium from exchangeable and non-exchangeable forms is not easily determined because of the reversible transformation from one form to the other that is assumed to occur in the soil. The behaviour of the different forms of soil potassium has been discussed concisely by Wiklander (15).

Investigations of New Brunswick and eastern Ontario soils have shown exchangeable potassium to be significantly correlated with uptake of potassium by crops grown in the greenhouse (8, 3). Under field conditions in Ontario, yield responses to potassium fertilizer were significantly correlated with exchangeable potassium values in tests with potatoes but not in tests with wheat, oats and corn (12). In other field tests in this province yield responses of tomatoes to potassium fertilizer were related to the amounts of exchangeable potassium in sandy loam soils but there was no such relationship within loam and clay loam groups (5). Non-exchangeable potassium has been found to be closely related to clay content of Ontario soils (14, 9).

The purpose of this investigation was to determine the supply of potassium in some Canadian soils varying in inherent characteristics and in past management. Amounts of water-soluble, exchangeable, and non-exchangeable potassium were used to evaluate potassium-supplying power of the soils. Non-exchangeable potassium was measured by (a) uptake by plants in pot tests; (b) repeated extraction with boiling nitric acid; (c) uptake by cation exchange resins, and (d) continuous leaching with 0.01 N hydrochloric acid. Some results relating to equilibrium between exchangeable and non-exchangeable forms of potassium are also presented.

¹Contribution No. 28, Soil Research Institute, Canada Department of Agriculture, Ottawa, Ont.

MATERIALS AND METHODS

Soils

Surface samples to plough depth were collected in the fall from 11 sites. Four soils, Charlottetown fine sandy loam (A) and (B) in Prince Edward Island, Caribou silt loam in New Brunswick, and Greensboro silt loam in Quebec are well-drained Podzols. Of five samples from eastern Ontario, Castor fine sandy loam, Granby sandy loam and Carp silty clay loam represent Dark Grey Gleysolic soils with improved drainage; Mountain loam is an imperfectly drained Brown Podzolic soil; and the Grenville clay loam is a well-drained Brown Forest soil. An unclassified well-drained loamy sand was collected near Fort William, Ontario. Cypress loam is a Brown chernozemic soil in southern Saskatchewan.

Prior to time of sampling, oats were grown on Charlottetown (A) and potatoes on Charlottetown (B), whereas the Cypress soil was fallowed. The remaining fields were in sod. The Charlottetown (B) soil had received liberal quantities of manure and fertilizer. The Caribou had received fertilizer whenever potatoes were grown. The Fort William soil had been manured in the past and more recent field observations indicated little or no response to potassium fertilizer by potatoes. No manure or fertilizer had been added to the Granby soil in the past 35 years.

Greenhouse

The soils were air-dried, passed through a sieve with a half-inch mesh and mixed. Five pounds of each soil were placed in glazed half-gallon pots. Ammonium dihydrogen phosphate (0.3726 gm./pot) was mixed with the soil and 0.1863 gram of the same chemical was placed in a layer at 2 inches from the surface in all pots. Two crops of oats, four of Sudan grass and three of oats were grown in succession over a period of 2 years in duplicate sets. Distilled water was added to maintain soil moisture at about field capacity. Additional nitrogen and phosphorus were added as required in the form of ammonium phosphate at times of seeding. Ten plants were grown in a pot and were harvested in vegetative stage. The roots of the first crop of oats and of the first and second crops of Sudan grass were harvested and washed. The harvested material was oven-dried, weighed and ground in a Wiley mill.

Laboratory

The plant material was ashed in muffle furnace at 500°C. The residue was dissolved in 10 millilitres 1 N HNO₃ and made to volume (250 millilitres) with 0.1 N HNO₃. Potassium was determined with a Model 146 Perkin-Elmer flame photometer, using lithium as an internal standard.

Preparation of soil samples and analyses for pH, organic matter, exchange capacity, base saturation, and exchangeable potassium were carried out using procedures described by Atkinson *et al.* (2). Mechanical composition was determined using the dispersion procedure and time intervals for settling given by Jackson *et al.* (7). Aliquots of the suspensions were removed with a pipette and dried in the oven. Water-soluble potassium was determined in 1:2 soil: water suspensions after shaking them for 2 hours and allowing them to stand for an additional 16 hours.

Repeated extraction of non-exchangeable potassium with boiling 1 N HNO_3 was carried out using the procedure described by Haylock (6) except for boiling time and soil: acid ratio. A 5-gram sample of soil was soaked overnight in 50 millilitres 0.1 N HNO_3 and leached with 5 additional 10-millilitre portions of the acid. The sample was placed in 50 millilitres 1 N HNO_3 , brought to a boil in 3.5 minutes, and boiled for 7 minutes. Potassium in the extracts was determined by flame photometry.

TABLE 1. — MECHANICAL COMPOSITION AND SOME CHEMICAL PROPERTIES OF THE SOILS

Soil	Sand 2.0- 0.05 mm.	Silt 0.05- 0.002 mm.	Clay <0.002 mm.	Organic matter	Ex- change capa- city	Base satura- tion	pH
	%	%	%	%	m.e./ 100 gm.	%	
Charlottetown (A)	49	41	10	5.6	10.1	63	5.0
Charlottetown (B)	54	35	11	4.3	8.6	52	4.6
Caribou	27	55	18	4.7	14.1	47	5.6
Greensboro	39	52	9	3.2	8.1	30	5.0
Castor	67	25	8	2.5	5.7	92	6.0
Mountain	41	44	15	3.2	10.2	64	5.3
Granby	56	32	12	5.2	13.8	100	7.6
Grenville	25	46	29	5.6	21.5	100	7.4
Carp	13	51	36	6.3	28.8	100	7.4
Fort William	77	17	6	2.5	9.5	58	5.6
Cypress	37	47	16	4.7	19.6	96	6.5

TABLE 2. — WATER-SOLUBLE AND EXCHANGEABLE POTASSIUM IN SOILS AND UPTAKE OF POTASSIUM BY PLANTS IN GREENHOUSE EXPERIMENT

Soil	Before cropping			After cropping			Uptake of K per pot	Uptake from ex- change- able K	Estimate of non-ex- changeable K ¹
	Water- soluble K	Ex- change- able K	K-sat- uration	Water- soluble K	Ex- change- able K	K-sat- uration			
	m.e. per 100 gm.		%	m.e. per 100 gm.		%			
Charlottetown (A)	0.020	0.13	1.3	0.005	0.06	0.6	137	45	0.08
Charlottetown (B)	.080	0.38	4.4	.007	.06	.7	374	76	.10
Caribou	.013	0.29	2.1	.003	.06	.4	326	62	.14
Greensboro	.009	0.11	1.4	.005	.05	.6	91	58	.04
Castor	.006	0.06	1.1	.005	.04	.7	80	23	.07
Mountain	.015	0.18	1.8	.004	.08	.8	245	36	.17
Granby	.006	0.10	0.7	.004	.08	.6	161	11	.16
Grenville	.011	0.25	1.2	.004	.16	.7	320	25	.27
Carp	.016	0.37	1.3	.009	.24	.8	808	14	.79
Fort William	.087	0.49	5.2	.003	.06	.6	350	109	— .03
Cypress	.079	1.07	5.5	.011	.33	1.7	1203	54	.63

Correlation coefficients:²Water-soluble K vs. % K-saturation— $r = 0.93^{**}$ % K-saturation vs. % uptake from exch. K— $r = 0.77^{**}$ Exchangeable K vs. uptake of K— $r = 0.91^{**}$ ¹Estimated non-exchangeable K = uptake of K by crops — (exchangeable K before cropping — exchangeable K after cropping).²Soil K values used are for samples taken before cropping.

Amberlite IR-120 was used in resin experiments. To 10 grams of soil, H-resin was added in an amount to provide ten times the exchange capacity of the soil. The soil-resin mixture was incubated in the moist condition at room temperature for 3 months and then air-dried. In another experiment 2 grams of H-resin was added to 1 gram of soil in 5 millilitres of distilled water and the suspensions were shaken for 1 week. Potassium in the mixture was replaced with 1 N neutral ammonium acetate without separation of soil and resin. The amount of exchangeable potassium in the soil before addition of resin was subtracted from the amount of potassium taken up by the resin to provide an estimate of non-exchangeable potassium.

The procedure described by Garman (4) was used to remove potassium by continuous leaching with 0.01 N HCl.

In the experiment relating to equilibrium between exchangeable and non-exchangeable potassium, samples were leached with 1 N neutral calcium acetate to obtain low level of exchangeable potassium. Two higher levels were established by leaching samples with 1 N neutral solution of calcium acetate containing appropriate amount of potassium. The samples were leached with alcohol and air-dried. A portion of the air-dried sample was moistened to about field capacity with distilled water, incubated in moist condition at room temperature for 13 months and air-dried. A portion of this incubated and air-dried sample was subjected to five cycles of wetting and drying at 70°C. Exchangeable potassium was determined and per cent K-saturation was calculated.

RESULTS AND DISCUSSION

The soils varied in reaction from acid to slightly alkaline, in clay content from 6 to 36 per cent, in organic matter from 2.5 to 6.3 per cent, and in exchange capacity from 5.7 to 28.8 m.e. per 100 grams (Table 1). These and other data for exchange capacity, following oxidation of the samples with hydrogen peroxide, showed that the contribution of organic matter to exchange capacity varied from 32 per cent in Caribou to 57 per cent in Castor soil.

Soluble and Exchangeable Potassium and Uptake by Plants

Exchangeable potassium before cropping was significantly correlated with uptake of potassium by plants (Table 2). This relationship occurred despite wide variations in the extent to which initial exchangeable potassium in the soils represented a source of potassium for the plants. For example, the decline in exchangeable potassium with cropping of Charlottetown fine sandy loam (B) amounted to 76 per cent of the total K-uptake, whereas the decline in the Carp silty clay-loam amounted to only 14 per cent of the uptake. Both soils contained about the same amount of exchangeable potassium before cropping, but the degree of K-saturation in the Charlottetown (B) was over three times that in the Carp sample. The amount of exchangeable potassium in Charlottetown (B) soil represented a major source of potassium supply whereas the amount of this form of potassium in the Carp soil was indicative of potassium-supplying power from non-exchangeable form. Exchangeable potassium values alone did not define the source of potassium.

Per cent K-saturation of Fort William soil was relatively high and the reduction in exchangeable potassium with cropping exceeded the recorded K-uptake. The high potassium-supplying power of the Cypress soil from exchangeable and non-exchangeable forms was reflected in the degree of K-saturation after cropping (1.7 per cent) which was at least double that for any of the other soils. In comparisons of soil samples with about the same clay content (Charlottetown (B) vs. (A); Fort William vs. Castor) water-soluble potassium and per cent K-saturation values differentiated the samples with respect to their capacity to supply potassium to plants. Furthermore, low concentration of potassium in Granby soil was in agreement with absence of fertilization in the past 35 years. Correlation coefficients show that per cent K-saturation before cropping was related to water-soluble potassium and to percentage of K-uptake derived from exchangeable form. In a previous study of 27 Ontario soils (10), water-soluble potassium, per cent K-saturation and $pK-\frac{1}{2}p$ (Ca + Mg) ratios were significantly correlated with each other, and reflected differences in potassium supply arising from past management. But such criteria, only, were not satisfactory for assessing potassium supply in soils with different capacities to release potassium from non-exchangeable form.

Non-exchangeable Potassium

Considerable potassium was released from non-exchangeable form during cropping (Table 2, column 10). Except for Cypress loam from western Canada, the estimated amounts of non-exchangeable potassium tended to increase with increasing clay content of the soils. These estimates

TABLE 3. — NON-EXCHANGEABLE POTASSIUM REMOVED FROM SOILS
BY REPEATED EXTRACTIONS WITH BOILING NORMAL NITRIC ACID

(Results expressed as m.e. per 100 grams of air-dry soil)						
Soil	K removed initially with 0.1 N HNO ₃	Non-exchangeable K released by repeated extractions (1 N HNO ₃)				Estimates of more soluble non-exch. K ¹
		1	2	3	4	
Charlottetown (A)	0.18	0.36	0.27	0.31	0.27	0.05
Charlottetown (B)	0.53	0.51	0.33	0.25	0.27	0.32
Caribou	0.41	0.39	0.22	0.15	0.15	0.31
Greensboro	0.17	0.26	0.17	0.17	0.16	0.10
Castor	0.12	0.26	0.12	0.10	0.10	0.18
Mountain	0.24	1.69	0.48	0.29	0.25	1.63
Granby	0.15	0.93	0.28	0.25	0.17	0.79
Grenville	0.30	1.08	0.59	0.38	0.36	0.93
Carp	0.45	3.56	1.82	0.76	0.38	5.00
Fort William	0.55	0.66	0.46	0.21	0.21	0.70
Cypress	1.06	1.70	0.93	0.60	0.37	2.12

Non-exch. K in N HNO₃ vs. greenhouse estimate (Table 2)— $r = 0.92^{**}$

¹Estimates for 9 of the soils represent K released by extractions 1 and 2 minus amounts released by extractions 3 and 4. Values for Carp and Cypress are totals for extractions 1, 2 and 3 each corrected for K released by extraction 4.

would tend to be lower than actual amounts since the harvested material did not include all roots. Soils containing more than equilibrium exchangeable potassium (12) would be expected to give low values for non-exchangeable potassium estimated from greenhouse results. The value for Charlottetown (B) was but slightly higher than that for Charlottetown (A), and the value for Fort William soil was negative.

Repeated extraction with boiling 1 N HNO₃. — The amounts of potassium removed by leaching with 0.1 N HNO₃ in preparing H-saturated samples (Table 3) exceeded the exchangeable level (Table 2) with the exception of Cypress loam. After two extractions with boiling 1 N HNO₃, potassium was removed at a fairly constant rate except from Carp and Cypress soils. The more soluble fraction of non-exchangeable potassium representing differences between amounts removed by earlier and later extractions (Table 3, column 7) was correlated with the estimate of non-exchangeable potassium obtained in the greenhouse experiment (Table 2, column 10). Nevertheless, there were discrepancies. Compared with greenhouse results, the boiling HNO₃ technique gave a relatively high value for the Mountain but underestimated non-exchangeable potassium in the Charlottetown (A) sample. The high value for the Carp soil was associated with high clay content. Non-exchangeable potassium was lower in the Podzol samples than in any of the others except Castor.

The amounts of non-exchangeable potassium in the fourth extraction varied much less between soils than did the amounts in the first and second extractions. Thus, correction for the amounts of the less soluble fraction had no marked effect on the relative magnitude of estimates of non-exchangeable potassium in soils containing the higher amounts. The quantities of potassium extracted at nearly constant rate were lower than those found

TABLE 4. — UPTAKE OF NON-EXCHANGEABLE POTASSIUM FROM SOILS BY H-RESIN

(Results expressed as m.e. per 100 gm. of air-dry soil)

Soil	Before cropping		After cropping	
	Incubated (i)	Suspension (s)	Incubation	Suspension
Charlottetown (A)	0.19	0.49	0.17	0.47
Charlottetown (B)	0.22	0.76	0.20	0.62
Caribou	0.24	0.61	0.16	0.54
Greensboro	0.11	0.37	0.11	0.37
Castor	0.18	0.46	0.19	0.43
Mountain	0.63	1.81	0.67	1.76
Granby	0.12	1.23	0.14	1.12
Grenville	0.59	1.23	0.61	1.20
Carp	3.28	5.38	3.08	4.82
Fort William	0.22	0.56	0.16	0.51
Cypress	2.40	1.70	2.02	1.59

Relation of resin values before cropping to other non-exch. K data:¹

H-resin (i) vs. Greenhouse— $r=0.99^{**}$ H-resin (i) vs. N HNO₃— $r=0.94^{**}$

H-resin (s) vs. Greenhouse— $r=0.86^{**}$ H-resin (s) vs. N HNO₃— $r=0.98^{**}$

¹Data for greenhouse and N HNO₃ are in Tables 2 and 3, respectively.

in New Zealand soils by Haylock (6) using a soil:acid ratio of 1 gm.:100 ml. and a 15-minute boiling period.

Uptake by exchange resins — Uptake of potassium by H-resin was greater in suspension than in incubated samples except for Cypress loam (Table 4). The difference was most pronounced with Granby soil. The coefficients show that non-exchangeable potassium removed from the uncropped soils by H-resin was correlated with uptake of this form of potassium by plants and with the more soluble fraction extracted with 1 N HNO_3 . The amounts of non-exchangeable potassium taken up by H-resin in suspension were usually lower after than before cropping. Recently, Arnold (1) presented evidence that H-resin removes relatively accessible non-exchangeable potassium from soils.

TABLE 5. — POTASSIUM REMOVED FROM SOILS BY CONTINUOUS LEACHING WITH 0.01 N HYDROCHLORIC ACID

Soil	K in successive increments of acid — litres				Total K removed (12 l.)	K removed by acid — exch. K Litres of acid	
	1	3	4	4		4	12
m.e./100 gm. of soil Before cropping							
Charlottetown (A)	0.16	0.049	0.023	0.018	0.25	0.08	0.12
Charlottetown (B)	0.46	.062	.033	.031	0.59	.14	.21
Caribou	0.31	.074	.038	.036	0.46	.09	.17
Greensboro	0.12	.018	.013	.013	0.16	.03	.05
Castor	0.07	.023	.021	.018	0.13	.03	.07
Mountain	0.21	.059	.041	.051	0.36	.09	.18
Granby	0.13	.074	.054	.041	0.30	.10	.20
Grenville	0.22	.190	.110	.090	0.61	.16	.36
Carp	0.33	.349	.172	.156	1.01	.31	.64
Fort William	0.57	.031	.036	.026	0.66	.11	.17
Cypress	1.17	.267	.200	.085	1.72	.37	.65
After cropping							
Charlottetown (A)	0.08	.023	.015	.013	0.13	.04	.07
Charlottetown (B)	0.09	.031	.023	.015	0.16	.06	.10
Caribou	0.08	.023	.021	.010	0.13	.04	.07
Greensboro	0.07	.018	.013	.013	0.11	.04	.06
Castor	0.06	.018	.015	.023	0.12	.04	.08
Mountain	0.09	.038	.033	.033	0.19	.05	.11
Granby	0.11	.095	.054	.056	0.32	.13	.24
Grenville	0.14	.162	.085	.090	0.48	.14	.32
Carp	0.26	.187	.149	.146	0.74	.21	.50
Fort William	0.10	.036	.026	.026	0.19	.08	.13
Cypress	0.33	.159	.100	.092	0.68	.16	.35

Relation of non-exch. K in 0.01 N HCl to other estimates:¹

4 l. 0.01 N HCl vs. Greenhouse — $r=0.93^{**}$ 12 l. 0.01 N HCl vs. H-resin (i) — $r=0.99^{**}$
 12 l. 0.01 N HCl vs. Greenhouse — $r=0.97^{**}$ 12 l. 0.01 N HCl vs. H-resin (s) — $r=0.76^{**}$
 12 l. 0.01 N HCl vs. N HNO_3 — $r=0.83^{**}$

¹ Estimates of non-exch. K by greenhouse, N HNO_3 , and resin techniques are in Tables 2, 3, and 4, respectively.

Continuous leaching with 0.01 N HCl — Data in Table 5 show that leaching with 1 litre of 0.01 N HCl usually removed amounts of potassium up to at least the exchangeable level. The amounts of non-exchangeable potassium removed by the first 4 litres of 0.01 N HCl (column 7) were considerably higher than the amounts removed by each of the two successive 4-litre increments (columns 4 and 5). The rate of removal of potassium from many of the samples became nearly constant after leaching with 4 litres of acid.

Cropping reduced the rate of removal of non-exchangeable potassium from several of the soil samples. McEwen and Matthews (13) reported that intensive cropping in the greenhouse had no apparent effect on rate of release of non-exchangeable potassium by carbonated water during a 36- to 108-hour percolation period.

Each of the 4-litre increments of acid removed more potassium from the well-managed Charlottetown (B) than from the (A) sample. The amounts of non-exchangeable potassium released by leaching Castor, Mountain, Granby, Grenville and Carp soils from eastern Ontario usually increased with increasing clay content of the samples. On the other hand, Cypress loam, a Brown soil, released considerably more of this form of potassium than did Mountain loam although both contained about the same amount of clay. After cropping, the final increment of acid removed potassium at a particularly low rate from the Podzol samples (Charlottetown, Caribou and Greensboro). Although not shown here, these differences between soils may be illustrated by plots of cumulative amounts of potassium removed with progress of leaching or time as employed by Garman (4) and Matthews and Smith (11).

The amounts of non-exchangeable potassium removed by 4-litre and 12-litre leaching of uncropped samples were correlated with greenhouse estimates of this form of potassium. As shown by the significant coefficients, non-exchangeable potassium removed by 12 litres of acid was correlated with that removed by plants, 1 N HNO_3 , and H-resin. In agreement with the results of Garman (4), there was a good relationship between the amounts of potassium removed by 12 litres of acid and the uptake by plants. The correlation coefficient (0.99) relating them was highly significant.

Equilibrium between Non-exchangeable and Exchangeable Potassium

The capacity of soils to supply potassium to plants depends not only on the quantities of the different forms present, but also on the rate at which the exchangeable potassium is replenished from a non-exchangeable source. It has been assumed that an equilibrium exists between exchangeable and non-exchangeable potassium, and that a low level of exchangeable potassium results in release of non-exchangeable form whereas a high level leads to fixation (15).

Data in Table 6, obtained by extracting exchangeable potassium immediately following leaching with 0.01 N HCl and then 95 per cent alcohol to remove excess acid, show a tendency for replenishment of the exchangeable form of potassium. As leaching progressed, the amounts of non-

exchangeable potassium released to exchangeable form became smaller. This slow rate of release to exchangeable form was also apparent in depleted soil samples following intensive cropping in the greenhouse. The increase in exchangeable potassium in cropped samples following moist incubation in the laboratory for 112 days was small and varied from 0.01 to 0.04 m.e. per 100 grams of soil. The greatest increase occurred in Cypress loam which had the highest degree of K-saturation (Table 2). Release of non-exchangeable potassium to exchangeable form in cropped samples was not affected by five cycles of wetting and drying at 70°C., except in Cypress loam where K-saturation increased from 1.7 per cent before, to 2.5 per cent after the treatment. Thus, even when the level of exchangeable potassium is low, release of non-exchangeable potassium to exchangeable form may be slow in soils already depleted of a more soluble portion of non-exchangeable potassium.

Data in Table 7 give some evidence of the existence of an equilibrium between exchangeable and non-exchangeable potassium. Samples with different degrees of K-saturation showed changes in this property upon incubation and wetting and drying and the direction of change was dependent on initial level established. In preparing these samples by leaching with 1 N neutral calcium acetate to obtain level 1 or with 1 N neutral solution of same salt plus potassium to obtain levels 2 and 3, removal of non-exchangeable potassium was unlikely. Moist incubation followed by wetting and drying of samples low in exchangeable potassium (level 1) resulted in release of non-exchangeable potassium and increase in per cent K-saturation in all but the Podzol soils. At higher degrees of K-saturation (levels 2 and 3), potassium was fixed and per cent K-saturation decreased in all soils except Cypress loam when the samples were incubated and wetted and dried.

TABLE 6. — EXCHANGEABLE POTASSIUM IN SOILS FOLLOWING CONTINUOUS LEACHING WITH 0.01 N HYDROCHLORIC ACID

Soil	Litres of acid		
	1 ¹	2.5	12
	m.e. K per 100 gm. soil		
Charlottetown (A)	0.027	0.015	0.012
Charlottetown (B)	.044	.042	.025
Caribou	.054	.050	.023
Greensboro	.032	.027	.024
Castor	.015	.015	.008
Mountain	.053	.026	.024
Granby	.062	.035	.028
Grenville	.131	.065	.048
Carp	.149	.068	.064
Fort William	.045	.029	.016
Cypress	.176	.083	.079

¹Leaching with 1 litre of acid removed more than the amounts of initial exchangeable potassium in 9 of the soils and all but 0.03 and 0.04 m.e. of this form in Grenville and Carp samples, respectively.

TABLE 7. — EFFECT OF MOIST INCUBATION AND REPEATED WETTING AND DRYING ON PER CENT K-SATURATION OF SOILS CONTAINING THREE LEVELS OF EXCHANGEABLE POTASSIUM

Soil	Per cent K-saturation					
	Not incubated; air-dry			Incubated 13 months; wetted and dried at 70°C. five times		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Charlottetown (A)	0.7	1.4	3.7	0.7	1.1	1.9
Charlottetown (B)	1.1	2.6	4.8	1.1	2.1	3.1
Caribou	1.4	1.8	3.0	0.8	1.0	1.4
Greensboro	1.1	2.1	3.0	0.9	1.2	1.5
Castor	0.3	1.5	2.5	0.8	1.3	1.8
Mountain	0.7	1.8	3.9	1.2	1.6	2.3
Granby	0.5	2.1	4.7	0.7	1.4	2.9
Grenville	0.6	1.4	2.4	0.8	1.1	1.4
Carp	0.6	1.9	3.8	1.1	1.5	2.5
Fort William	1.0	1.7	3.2	1.3	1.6	2.5
Cypress	1.7	2.4	4.4	2.9	3.3	4.5

Recently, Matthews and Sherrell (12) related the amounts of exchangeable potassium in oven-dry and moist samples of Ontario soils by means of regression analysis and reported that the average value for K-saturation at equilibrium was 1.11 ± 0.12 per cent. The regression equation relating per cent K-saturation before and after incubation plus wetting and drying of six Ontario soils included in the present investigation was $Y = 0.0646 + 0.4674 X$. The estimated K-saturation (1.21 per cent) at equilibrium was in good agreement with that obtained by the authors cited.

Per cent K-saturation at which potassium appeared to be in equilibrium in the Podzol soils was 0.7 in Charlottetown (A), 1.1 in Charlottetown (B), 0.8 or less in Caribou, and 0.9 or less in Greensboro. Hence, there was some evidence that equilibrium might occur at a slightly lower degree of K-saturation in Podzols than in the other soils. The data show that the degree of K-saturation, at which equilibrium might be expected to occur, was considerably higher in Cypress loam, a Brown soil, than in the others and was at least 4.5 per cent. Although the results are indicative of a reversible reaction between exchangeable and non-exchangeable potassium, equilibrium was not attained in most of the samples under the conditions of this experiment. Nevertheless, the estimated degree of K-saturation in the Ontario samples (1.21 per cent) was nearly identical with the mean degree of K-saturation (1.15 per cent) in 602 surface samples collected from old pastures and analysed by the Ontario Soil Survey (10). Potassium in the latter samples would be expected to approach equilibrium since the fields sampled had not been cropped intensively and had received little or no fertilizer.

The observed degree of K-saturation (Table 2) relative to that expected at equilibrium was indicative of residual fertilizer in Charlottetown (B) and Fort William samples and of a high rate of release of non-exchangeable potassium in Cypress soil. But per cent K-saturation and other in-

tensity measurements did not reflect the marked differences in potassium-supplying power of soils differing from each other in clay content such as Castor and Carp samples. To assess potassium-supplying power of different soils, estimates of the amounts of non-exchangeable potassium expected to be released must also be considered.

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EFFECTS OF RUN-OFF PREVENTION AND LEACHING WATER ON A SALINE SOIL¹

FRED M. SANDOVAL, C. W. CARLSON, R. H. MICKELSON AND LEO BENZ²
United States Department of Agriculture

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ABSTRACT

A 4-year study was conducted on the effects of precipitation management on salt movement and spring wheat yields on an imperfectly drained saline silt loam in the northern Red River Valley of North Dakota. Partial leaching by artificially applied water at the beginning of the experiment was compared to leaching benefits by impounded precipitation. Average monthly water table fluctuated from 2 to 11 feet with rainfall and was usually lowest in late winter or spring and highest during the summer. Average yearly precipitation is 20 inches.

Impounded precipitation was found effective in partially desalinizing the soil. Summer rain was more effective than winter precipitation. Wheat yields were inversely related to soil salinity with the highest correlation coefficients occurring on springtime data for the 6- to 16-inch depth.

INTRODUCTION

Crop production on many thousands of acres of crop land in the Red River Valley of North Dakota is reduced by high concentrations of salts. A major area, in excess of 200,000 acres, is found in Grand Forks County west of Grand Forks, North Dakota. The salinity problem is associated with high water table conditions. Considerable acreage of saline lands in the Red River Valley of Canada has also been reported (2).

The Red River Valley is the glacial lake plain from glacial Lake Agassiz which occupied the area following the ice ages. Topography of the area is almost flat having only a foot or two slope per mile.

The area is characterized by an undulating microrelief which forms a fracture pattern of gentle ridges and depressions (4). Relief differences between ridges and depressions, in most cases, are from 1 to 2 feet. Distance between the lowest (depression) and highest (ridge) points is variable with a range of 300 to 500 feet. Run-off from ridges is frequently impounded in depressions. In slightly to moderately affected land, salts are concentrated on ridges while the associated depressions are relatively nonsaline. Salt accumulations on the ridges are apparently due to a comparatively greater upward than downward movement of soil moisture.

Numerous artesian wells are present in the area. These artesian waters are saline and originate from the Dakota geologic formation which underlies the entire valley (5).

The climate is subhumid (1). Annual precipitation is about 20 inches, 60 per cent falling from May 1 through August 31. Average monthly temperature is 4.4°F. for January and 70.7°F. for July. Average frost-free period is 126 days.

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²Soil Scientist, Soil Scientist, Agricultural Engineer and Agricultural Engineer, respectively, Western Soil and Water Management Branch, Agricultural Research Service, U.S. Department of Agriculture, Mandan, and Grand Forks, North Dakota.

Principal objective of the experiment was to evaluate soil salinity changes on a typical ridge that might be brought about where natural precipitation was impounded or supplemented with additional water, compared to allowing run-off to adjacent depressions. A secondary objective was to evaluate spring wheat response to soil salinity.

MATERIALS AND METHODS

In the fall of 1955, an experiment was initiated on a saline ridge in a moderately affected area near Grand Forks. Treatments chosen were (A) check, precipitation not impounded; (B) precipitation impounded; (C) precipitation impounded plus 9 inches of supplemental leaching water, and (D) precipitation impounded plus 18 inches of water. Leaching water was applied only in the autumn of 1955, at the beginning of the experiment, to accelerate downward salt movement and to determine how permanent reductions derived might be. Each treatment was on a nearly-level plot 20 feet square replicated four times in a randomized block design. All plots were diked on four sides with the exception of those for the check treatment which had the lower end open to allow run-off. Plots were separated by 14-foot alleyways.

A hard red spring wheat (Selkirk), fairly sensitive to salinity, was seeded on all plots each year and fertilized with 15 pounds N and 30 pounds P_2O_5 per acre. Border areas or alleyways were uncropped and maintained free of weeds.

Soil samples were collected in the fall of 1955 before and after applying leaching water, every spring prior to planting and every autumn following harvest. Composite soil samples from four holes per plot were obtained for the 0-6, 6-16, 16-28, 28-38, 38-48, and 48-60 inch depths. A systematic sampling plan was followed so that holes were never closer than 2 feet to any previous sampling hole. Sample holes were back-filled to correspond with soil horizons and tamped to prevent water columns from forming.

TABLE 1. — DESCRIPTION OF A PROFILE OF GLYNDON SILT LOAM SALINE PHASE

Horizon	Depth (inches)	Description
A ₁ p	0-5	Black (10YR 2/1) ¹ silt loam; fine crumb structure; many small white salt segregations, strongly calcareous ²
A _{ca}	5-12	Very dark greyish brown (10YR 3/2) silt loam; very fine crumb structure; gypsiferous; very strongly calcareous
C _{ca}	12-23	Greyish brown (2.5Y 5/3) silt loam; weak, very fine crumb structure; frequently gypsiferous; very strongly calcareous
C ₁	23-48	Light olive brown (2.5Y 5/4) silt, weak, very fine crumb structure; some grey and yellowish brown mottles; slightly calcareous
C _{zg}	48-60	Light olive brown (2.5Y 5/4) silty clay loam; fine lacustrine varving; numerous rusty coloured mottles and iron concretions; slightly calcareous

¹Munsell notations for moist soil

²From reaction with dilute HCl

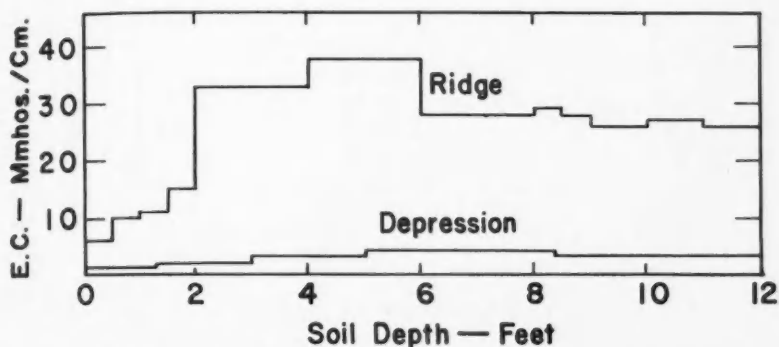


FIGURE 1. Comparison of soil salinity at the ridge and an associated depressional area.

Soil salinity was evaluated by measuring electrical conductivity of extracts from saturated soil paste. Other laboratory determinations were also made using procedures recommended in U.S.D.A. Handbook 60 (8).

Measurements of the water table were obtained through 4-inch diameter perforated observation wells extending 12 feet into the ground. Two wells, 400 feet apart, were used — one in the ridge and the other in an adjacent depression. In the spring of 1958, water stage recorders were installed on the wells to obtain a continuous record of water table fluctuations.

RESULTS AND DISCUSSION

Table 1 describes the soil profile of the ridge area used for the experiment. The imperfectly drained soil is identified as Glyndon silt loam saline phase, is developed from deep lacustrine sediments and morphologically classified as a solonchak (7). The soil was gypsiferous and calcareous to the surface. Chemical composition of the water and saturated extracts of the soil are shown in Table 2. Principal soluble salts near the surface were magnesium and calcium sulphate. Both magnesium and sodium increased considerably with depth. At lower depths chlorides were dominant followed by sulphates. The soil was slightly alkaline. Exchangeable sodium percentage ranged from 6 at the surface to 20 at 2 feet. Bicarbonate content was negligible. The soil is classed as a saline-sodic soil (8).

A comparison of salinity of the ridge and an associated depression is illustrated in Figure 1. Sampling sites were 400 feet apart. The ridge was 10 inches higher (surface elevation) than the depression site. The ridge area is highly saline to a depth of 12 feet and the depression comparatively nonsaline. The highest salinity in the ridge was between 2 and 6 feet depth.

Table 2 also gives the composition of the shallow ground waters under the ridge or experimental area and under an associated depression. Four years of observation, at the same site, showed that salinity of the ridge water, expressed as electrical conductivity, varied from 29 to 50 millimhos per centimetre. Average conductivity for the period was 45 millimhos (about 37,000 p.p.m.). Water chemistry was closely related to chemistry of the ambient soil. Magnesium and sodium chlorides were the predominant

TABLE 2. — COMPOSITION OF SALINE SOIL AND SHALLOW GROUND WATERS¹

Depth	pH	Elect. cond.	Saturation extract						Exch. Na	Soluble Na
			Ca	Mg	Na	SO ₄	Cl	C.E.C.		
			mmhos. /cm.	me/L	me/L	me/L	me/L	me/ 100g.		
inches					SOIL				%	%
0- 5	7.5	6.2	28	28	33	72	6	38	6	37
5-12	7.7	9.8	24	48	71	120	17	27	11	49
12-16	7.8	10.3	15	44	77	90	42	23	14	57
16-23	7.9	15.2	12	64	112	72	112	16	18	60
23-48	7.2	32.5	26	195	212	120	313	14	20	49
48-60	7.2	37.6	31	261	232	141	380	18	21	44
GROUND WATER										
Ridge	7.8	45.4	32	319	293	214	432	—	—	45
Depr.	8.1	1.2	7	4	3	6	2	—	—	12

¹Soil sampled October 12, 1955; water samples collected May 18, 1956

salt constituents. On the basis of chemical equivalents, magnesium content was ten times greater than calcium. Salinity of the ground water tended to decrease as the water table neared the surface. The decrease was probably due to dilution effects of percolating rainfall.

Fluctuation of the ridge water table during the period of experimentation is illustrated in Figure 2. No measurements were made in early 1956 and during the first 4 months of 1957 due to inoperative wells. The values plotted represent average water table levels for the month. Monthly precipitation is also plotted. Total precipitation for each year is given at the bottom of the figure. Water tables rose following periods of precipitation. The lowest level of the water table occurred in February, March, or April. The lowest water table level recorded was 11 feet from the soil surface. The average level was 6.8 feet.

Figure 3 illustrates the influence of rainfall on water table fluctuations during an 11-day period, May 30 to June 9, 1958. Three rains of 1.32, 0.45, and 1.40 inches fell on May 30, June 3, and June 4, respectively. Approximately 24 hours after the first rain, the water table at 6.9 feet started to rise. It rose to 5.9 feet by noon, June 1, and levelled off somewhat at 5.6 feet on the morning of June 2. Following rains on June 3 and 4, the water table rose again until it reached 3.4 feet where it remained for 28 hours before starting to drop. Between June 6 and 9 it receded to 4.4 feet. Rainfall markedly influenced the water table.

Slight rises in the water table were observed immediately following sub-soil thawing in the spring which were difficult to attribute directly to rainfall or to run-off from melt waters. Run-off from the snowpack takes place before the sub-soil thaws. For example, between April 16 and 26, 1958, the water table rose gradually from 8.8 to 6.9 feet from the surface.

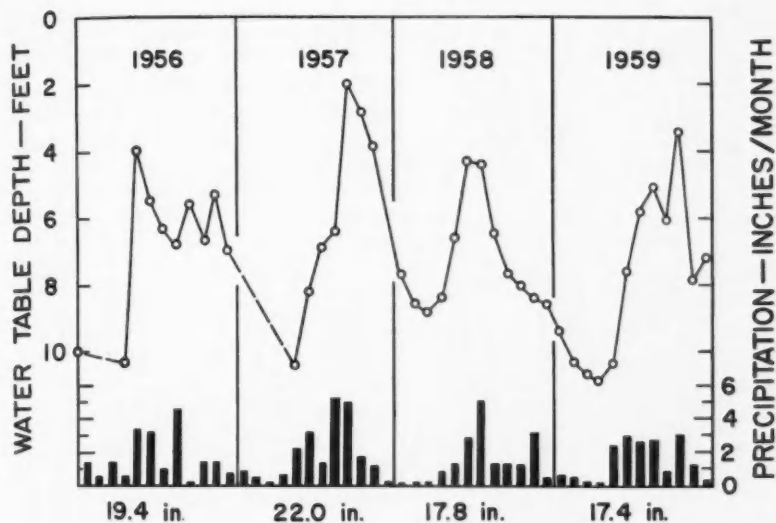


FIGURE 2. Average monthly water table and relationship to monthly precipitation.

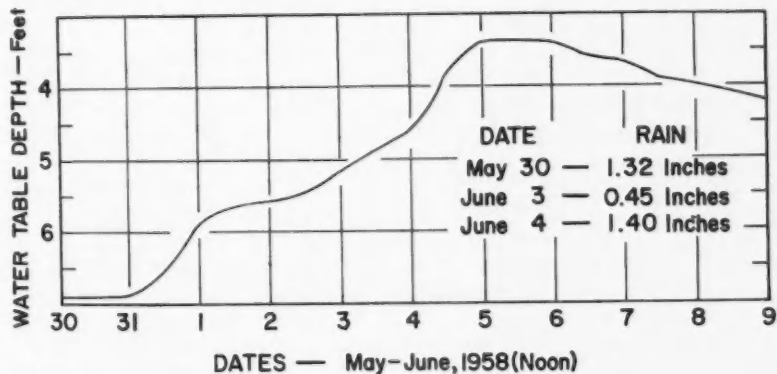


FIGURE 3. Water table fluctuations during an 11-day period, May 30 to June 9, 1958.

No precipitation fell during this period. A shower of 0.16 inch recorded on April 11 was inconsequential. Other workers (3, 6) have suggested that frozen layers of soil acquire water beyond that which they are able to hold against the force of gravity under frost-free conditions. This acquisition of extra water is attributed to capillary movement under a temperature gradient. This phenomenon could account, partly, for the drop in the water table in late autumn and rises in the spring upon thawing.

TABLE 3. — TREATMENT EFFECT ON SOIL SALINITY OF SEVERAL DEPTHS OVER A 4-YEAR PERIOD. VALUES ARE AVERAGES FOR FOUR REPLICATIONS

Treatment	Sampling date ¹	Soil depths—inches					
		0-6	6-16	16-28	28-38	38-48	48-60
		Electrical conductivity in millimhos/cm.					
A. Check; precipitation not impounded	18-10-55	10.0	13.9	21.8	n.d. ²	n.d.	n.d.
	7- 5-56	9.2	10.9	19.0	29.0	n.d.	n.d.
	1-10-56	8.3	11.4	16.2	25.1	26.9 ³	
	30- 4-57	8.9	11.4	18.9	25.4	28.8	27.8
	24- 9-57	7.3	10.2	15.7	25.6	31.4	30.8
	29- 4-58	10.4	12.9	24.9	32.7	37.0	35.4
	25- 8-58	11.9	12.8	20.8	38.4	38.9	37.8
	28- 4-59	12.7	13.3	20.5	29.5	33.8	32.7
12- 8-59	10.0	11.6	21.4	29.9	33.4	29.7	
B. Precipitation impounded	18-10-55	8.4	11.9	16.5	n.d.	n.d.	n.d.
	7- 5-56	8.3	11.1	23.2	30.1	n.d.	n.d.
	1-10-56	6.9	9.4	16.9	26.0	31.4 ³	
	30- 4-57	7.7	10.6	18.8	27.7	32.2	31.5
	24- 9-57	4.5	6.2	13.1	20.0	28.8	31.5
	29- 4-58	5.4	8.6	19.1	30.6	39.4	36.8
	25- 8-58	5.6	7.1	16.3	30.6	40.7	39.4
	28- 4-59	7.7	9.4	18.6	29.0	34.1	33.9
1- 8-59	5.5	7.4	19.3	28.6	32.4	34.2	
C. Precipitation impounded plus 9 inches of water ⁴	18-10-55	8.5	12.9	23.2	n.d.	n.d.	n.d.
	4-11-55	5.8	8.6	12.5	n.d.	n.d.	n.d.
	7- 5-56	8.7	9.1	15.5	25.6	n.d.	n.d.
	1-10-56	5.1	6.8	11.6	20.6	27.8 ³	
	30- 4-57	6.7	8.4	14.1	22.8	26.2	29.9
	24- 9-57	4.2	5.8	8.5	16.6	26.5	28.2
	29- 4-58	5.1	8.0	15.9	27.5	34.4	36.4
	25- 8-58	6.1	7.4	13.0	30.0	29.5	36.9
28- 4-59	7.7	8.9	14.6	23.4	30.0	31.7	
12- 8-59	5.1	6.8	11.6	21.8	30.6	32.6	
D. Precipitation impounded plus 18 inches of water ⁴	18-10-55	10.0	14.7	25.9	n.d.	n.d.	n.d.
	4-11-55	4.2	4.9	7.7	n.d.	n.d.	n.d.
	7- 5-56	6.5	6.9	11.2	18.8	n.d.	n.d.
	1-10-56	5.6	7.1	11.2	18.7	27.3 ³	
	30- 4-57	6.8	8.0	14.1	21.6	26.5	28.3
	24- 9-57	4.1	5.7	9.8	16.3	25.6	28.7
	29- 4-58	5.1	7.4	15.6	26.1	33.4	35.5
	25- 8-58	5.8	6.8	15.2	24.1	35.2	36.5
28- 4-59	7.4	9.2	17.1	24.0	29.7	30.0	
12- 8-59	5.6	7.0	13.0	25.2	28.4	31.3	

¹Day-month-year²Not determined³Value represents 38- to 60-inch depth⁴Supplemental water applied October 20, 1955, only

The foregoing discussion on ground water has been for the ridge or crest of an undulation where the experiment was conducted. Adjacent depressional characteristics might also be described briefly for comparison. Ground waters in the depressional area were low in salts compared to waters of the saline ridge (see Figure 1). The water table in the depression areas was usually 6 to 10 inches closer to the surface than in the experimental or ridge area.

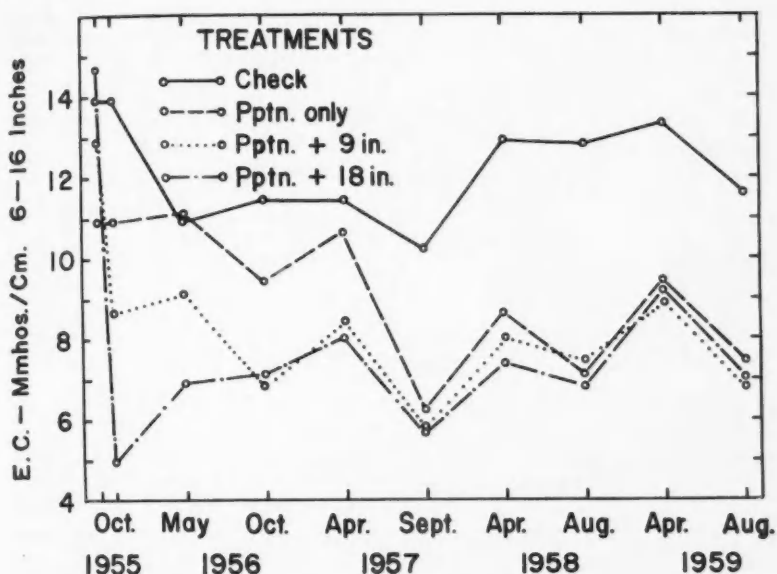


FIGURE 4. Effect of treatments on soil salinity at 6- to 16-inch depth over 4-year period.

Table 3 summarizes effects of treatments on changes in soil salinity for several depths during 4 years. Initial application of 18 inches of water (Treatment D) reduced salinity from 10.0 to 4.2 millimhos/cm. in the surface and from 14.7 to 4.9 millimhos in the 6- to 16-inch depth. Nine inches of water (Treatment C) reduced salinity of the surface from 8.5 to 5.8 millimhos/cm. and from 12.9 to 8.6 millimhos in the 6- to 16-inch depth. Supplemental leaching waters markedly reduced salinity. Comparable reductions were accomplished in 2 years by impounding precipitation (Treatment B) alone. Soil salinity to 16 inches was lower after the second year for all treatments receiving impounded rainfall than for the check treatment which allowed run-off.

The largest reduction of salts for all treatments occurred in 1957. This decrease was apparently due largely to 5 inches of rain which fell between August 31 and September 2. The water table rose to the surface by September 5; it receded to 2.2 feet by September 20. Soil samples were collected September 24.

Data from Table 3 for the 6- to 16-inch depths is graphically illustrated in Figure 4. Precipitation alone is apparently sufficient in the area to decrease salinity appreciably.

Increases in salinity to 28 inches depth were observed to take place every year between autumn and spring. Whether or not salts migrated upwards during winter in frozen soil was not definitely established. Movement of salts towards the surface during winter is apparent and may be

TABLE 4. — SOLUBLE SODIUM STATUS OF THE SOIL FOR THREE DEPTHS, AT THE BEGINNING AND AT TERMINATION OF THE EXPERIMENT. VALUES ARE MEANS FOR FOUR REPLICATIONS.

Treatment	October 1955			August 1959		
	Soil depths in inches			Soil depths in inches		
	0-6	6-16	16-28	0-6	6-16	16-28
	Milliequivalents sodium per litre of saturated soil extract					
A	51	82	127	68	82	138
B	43	69	104	29	52	129
C	45	85	157	24	50	76
D	60	98	163	28	44	92

associated with moisture movement as discussed previously. Salinity reductions took place between spring and autumn. For example, in 1956 (Table 3), Treatment B for 6- to 16-inch depth, electrical conductivities went from 11.1 to 9.4 millimhos between spring and autumn. Conductivity increased over the winter to 10.6 millimhos on April 30, 1957. By September 24, 1957, salinity was reduced to 6.2 millimhos; however, this reduction was partly offset by the subsequent winter increase and on April 29, 1958, conductivity was 8.6 millimhos. This trend, observed for all treatments, was greatest where rain was impounded and persisted to termination of the experiment.

Desalinization reflected effects of seasonal precipitation. The data suggest that summer precipitation is more effective than winter precipitation under the conditions studied. Leaching benefits from snow melt waters may be small while sub-soils are still frozen. Soils of the area start to freeze about November 1 and by March 1 the frost has reached a depth of 4 to 5 feet during most winters. Generally, the soil does not completely thaw before May 1. Although spring soil samples were collected while the sub-soil was still frozen, snow melt waters had run off.

Soluble sodium status of the soil for three depths, at the beginning and termination of the experiment, is reported in Table 4. There was a slight gain in sodium where rain was not impounded. Sodium salts were reduced in the 0- to 16-inch depth by impounding rainfall alone and they were reduced further by using supplemental water in addition to impounding rain. The greatest decrease was obtained when 18 inches of supplemental water was applied at the initiation of the experiment. Exchangeable sodium percentage can be expected to decrease as desalinization progresses.

Soil pH was not changed by the reductions of salinity which took place. There were no visual changes in soil physical properties during the experimental period.

Effect of treatments on wheat yields and grain test weights is summarized in Table 5. Wheat yields were increased by impounding precipitation; yields were further increased by supplemental water applications to remove salt. Mean 4-year yield for the check treatment was 6.7 bushels

TABLE 5.—EFFECTS OF TREATMENT ON WHEAT YIELDS AND GRAIN TEST WEIGHTS

Treatment	1956		1957		1958		1959		Means	
	Yield	Test wt.	Yield	Test wt.	Yield	Test wt.	Yield	Test wt.	Yield	Test wt.
	bu./a.	lb./bu.	bu./a.	lb./bu.	bu./a.	lb./bu.	bu./a.	lb./bu.	bu./a.	lb./bu.
A	9.4	50	8.9	46	6.0	56	2.5	48	6.7	50
B	9.8	50	10.8	45	27.5	60	13.3	52	15.3	52
C	12.0	51	11.3	48	28.3	61	13.0	52	16.1	53
D	26.2	54	18.4	50	30.8	60	13.3	53	22.2	54
LSD										
.05	7.2		5.3		3.3		1.8		3.6	
.01	10.4		7.6		4.7		2.6		5.2	

per acre. Where precipitation was impounded, the 4-year mean was 15.3 bushels, increasing to 22.2 bushels where impounded precipitation was supplemented initially with 18 inches of water. There were no significant differences among treatments in 1958 and 1959 where precipitation was impounded.

The beneficial effects of impounded precipitation on yields were not manifested until 1957 or the second year. By 1958 effects were quite evident. Treatments where precipitation was held (Treatments B, C, and D) yielded about the same in 1958 and 1959; these were significantly higher yields than the check treatment (Treatment A) where run-off was allowed. Grain yields reflect climatic influences. Climate in 1958 was favourable. This factor, coupled with the heavy rains in the fall of 1957 contributed to high yields. Effects from salinity are closely tied to soil moisture supplies.

Grain test weights were depressed by soil salinity. The lightest grain, averaging 50 pounds per bushel, was produced where salinity was highest and yields lowest (*see* Table 5). Conversely, the heavier grain was produced where salinity was lowest.

Statistical analyses of the data indicate that wheat yields were significantly correlated negatively with soil salinity. Correlation was highest for yields and soil salinity in the spring at the 6- to 16-inch depth. The relationship is curvilinear. Soil salinity in the spring and grain yields for individual plots, for all years, are represented in Figure 5. The curve is calculated from 4 years of pooled data. The equation is $Y = 68 - 8(EC) + 0.24(EC)^2$. The multiple correlation coefficient, R , is -0.79 , and is slightly higher than the simple linear correlation coefficient, $r = -0.75$. Although the experiment was conducted under saline conditions, the curve is extrapolated to indicate expected yields under average nonsaline conditions.

CONCLUSIONS

Ridges or crests of the gently undulating topography of the area were considerably more saline than associated depressions. Soil salts were largely water-soluble. Impounding natural precipitation was effective in partially

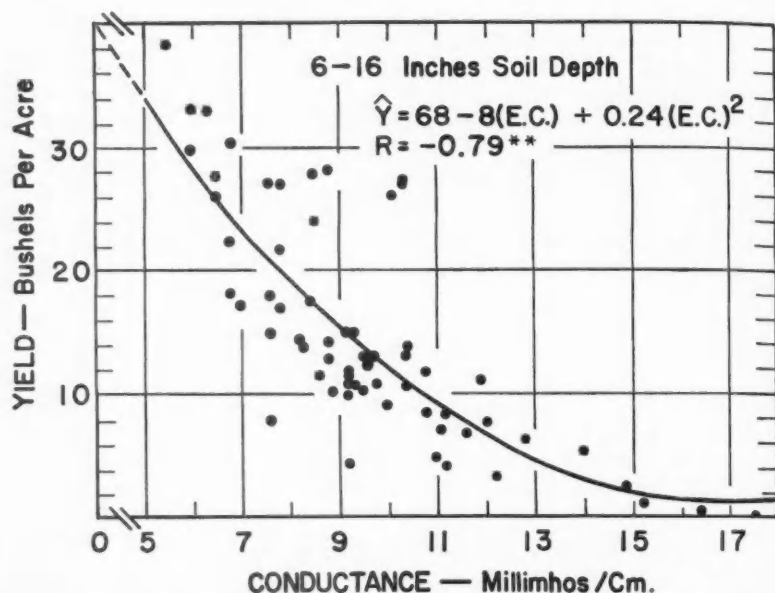


FIGURE 5. Regression of wheat yields with increased soil salinity of 6- to 16-inch depth at planting time using individual plot values.

desalinizing the silt loam profile on the ridge. However, effectiveness of improvement was restricted somewhat by position and fluctuations of the water table. Salt accumulations took place between autumn and spring. Rainfall occurring between spring and harvest was more effective in desalinizing the soil than winter precipitation. Salt reductions were accompanied by reduction of soluble sodium.

The water table was markedly influenced by rainfall. Water table rises in spring were partially attributed to moisture leaving frost zone upon thawing.

Wheat yields were significantly reduced by soil salinity and the relationship could be expressed by a quadratic equation. Grain weights were reduced by soil salinity.

ACKNOWLEDGEMENTS

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YELLOW MOTTLES IN SOME POORLY DRAINED SOILS OF THE LOWER FRASER VALLEY, BRITISH COLUMBIA¹

J. S. CLARK, C. A. GOBIN AND P. N. SPROUT²

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ABSTRACT

Chemical and mineralogical studies were made of yellow mottles and brown tubular formations in some strongly acid, poorly drained soils of the Lower Fraser Valley, British Columbia. The yellow mottles contained a high proportion of sulphur and were found to be composed mainly of jarosites, iron polysulphides and quartz. The brown tubes were composed of soil particles cemented by iron sulphates, sulphides, and oxides produced in the vicinity of plant roots. The mottles occur in soils adjacent to tidal rivers and it is postulated that the yellow mottles were formed by the reduction of sulphates in the seepage waters from these rivers to sulphides and the subsequent oxidation of the sulphides to the basic ferric sulphate.

INTRODUCTION

Organic and Gleysolic soils predominate on the poorly drained deltaic deposits in the lower Fraser Valley (17). As would be expected, the majority of the soils exhibit characteristics of poor drainage and are gleyed and mottled in the subsoil. During a soil survey of this area, it was observed that many of the soils in the lower Nicomekl and Serpentine River Valleys had a profusion of intense yellow mottles scattered throughout the lower horizons. In some cases, the mottles appeared as flecks or as coatings on the soil peds but, in others, the mottles occurred as tubular formations in old root channels. Brown tubular mottles and flecks were also observed both in soils containing the yellow mottles and in those in which no yellow mottles were present. Since the tubular formations and, in some cases, the yellow flecks, could be separated from the soil, a study was made of their chemical composition in order to determine their nature and origin.

OCCURRENCE OF YELLOW MOTTLES

The more recent delta of the Fraser River in British Columbia is a low-lying level area with elevations ranging from sea-level to about 25 feet; in many areas the land is diked against the rivers and the sea.

Mineral soils and soils having an organic surface layer have developed on these low-lying deltaic and channel deposits, the texture of which may be silty clay, silty clay loam or, even, loam or sand. The soils that originally were surfaced with organic deposits have been modified by cultivation to such an extent that, in many cases, the surface horizon now consists of the organic material mixed with the underlying mineral soil. The mineral soil immediately below the organic horizons is darkly stained with organic matter, particularly along the cracks in the otherwise massive soil. With depth the intensity of staining decreases and the soil becomes olive grey in colour. The fine textured mineral soil is massive but, owing to the montmorillonitic nature of the clays³, the soil becomes deeply cracked during the dry part of the year.

¹Contribution from the Department of Soil Science, University of British Columbia, Vancouver, B.C. Part of this work constituted the undergraduate essay submitted by the second author in partial fulfilment of the requirements of the B.S.A. degree, University of British Columbia.

²Formerly Assistant Professor, University of British Columbia, now Research Officer, Canada Department of Agriculture, Vancouver, B.C.; Student, Department of Soil Science, University of British Columbia; and Soil Surveyor, B.C. Department of Agriculture, Kelowna, B.C., respectively.

³Clark, J. S., et al. Clays in some British Columbia Soils. Unpublished data.

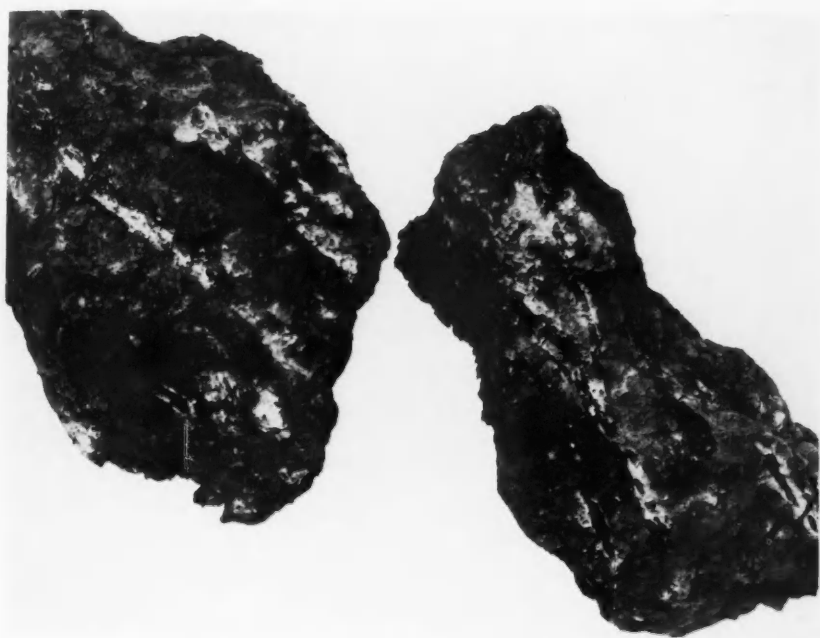


FIGURE 1. Yellow tubes in root channels imbedded in olive grey matrix.



FIGURE 2. Brown tubes.

The yellow mottles and brown tubes were present in those organic and mineral soils close to tidal rivers and the sea. These soils are subject to seepage of sea water and have high conductivity values throughout the profile or in the subsoil; in severe cases salt efflorescence may occur on the soil surface. As pointed out previously, soils were observed in which both the yellow mottles and the brown tubes were present as well as those in which only the yellow mottles or brown tubes could be found. No consistent pattern in this regard, however, was observed.

The yellow mottles were most commonly present as small masses imbedded in the matrix of the soil, or as a coating over the peds, especially where cracks were evident. Often the yellow coatings were themselves covered with a thin, reddish brown coating. The yellow mottles were also present in the form of tubes and appeared to result from the accumulation of the yellow material around old roots and other plant remains (Figure 1).

The brown tubes were more prevalent in most of the profiles and some examples may be seen in Figure 2. The brown tubes were generally larger than the yellow tubes and, owing to their slightly hard consistence, some of the brown tubes could be removed readily from the soil in lengths up to 4 inches.

In organic soils, the yellow mottles occur most commonly in the upper 8 inches of mineral soil which underlies a compacted layer of peaty muck. In mineral soils, the yellow mottles were commonly observed in the gleyed subsoils at a depth of 18 to 36 inches. The brown tubes occur at the same depths as the yellow mottles but are also found, although in fewer numbers, at depths down to 42 inches. In almost all cases, the texture of the matrix in which both formations are found is a silt loam.

The level of the water table in the soils changes markedly through the year. As they occur in low-lying areas, the soils are frequently covered with water throughout the wet, mild winter. During the dry summer, the water table may drop to a depth of 24 inches or more.

MATERIALS AND METHODS

The locations of the four soils used for this study are shown in the map in Figure 3 and detailed descriptions of the soils are given in the appendix. The samples for analysis were selected from a depth of 16 to 24 inches in all soils. The yellow mottles and the brown tubes were removed carefully from the soil by breaking open the soil clods and picking out the materials. Soil adhering to the surface of the brown tubes was removed by scraping the tubes with a knife. The samples were air-dried in the field and stored in tightly closed containers. Composite samples of the whole soil at the same depth were also obtained and these were air-dried and crushed to pass through a 2-millimetre sieve.

For the determination of total sulphur, the samples of soil, the yellow mottles and the brown tubes were crushed to pass 0.5 millimetre. Exactly 1 gram of the soil and 0.25 gram of the mottles and tubes were fused with Na_2CO_3 and NaNO_3 according to the method of Jackson (6, p. 322). After

fusion, the melt was dissolved in hydrochloric acid, dehydrated, and the amount of SiO_2 determined in the usual way with H_2F_2 (8). Sulphate was determined both by the BaSO_4 method (19) and by the colorimetric barium chloroanilate method (2) after removal of cations by resin exchange. The results obtained by the colorimetric method were only slightly higher than those obtained by precipitation of BaSO_4 . Owing to difficulties encountered in filtering the sulphate precipitate, the colorimetric method was considered the more reliable. The total iron content was determined by the ortho-phenanthroline method (18) and aluminium by the aluminon method (9). After separation of iron and aluminium by precipitation with NH_4OH and NH_4Cl , and of sulphate with an anion exchange resin, calcium was determined with the flame photometer.

The pH of the soil was measured, using the glass electrode and 1:1 soil:water ratio. The organic matter content was determined by wet oxidation with dichromate (14). For the determination of conductivities a 1:1 water:soil extract was employed.

The water-soluble sulphates were determined by extracting the mottles with water, using a 1:25 solid:water ratio. The aqueous extracts were tested for sulphates with BaCl_2 and, as no sulphate was detected, a quantitative determination of the water-soluble sulphate was not made. The mono-sulphidic sulphur content was determined by boiling the samples in dilute HCl and collecting the liberated H_2S in a cadmium-zinc acetate solution. The liberated H_2S was then determined by treatment with excess iodine and the excess iodine titrated with $\text{Na}_2\text{S}_2\text{O}_3$ (20). The digestion of the mottles with concentrated HCl and tin was used to determine the total oxidizable sulphur (20).

The free sulphur in the yellow mottle sample was determined by extraction with carbon bisulphide (19) and the extracted sulphur was precipitated as BaSO_4 after oxidation. The N-(4,4'-dimethoxybenzohydrilidene) benzylamine method of Ory *et al.* (12) was also used for the determination of free sulphur.

The X-ray analyses of powder specimens were made using a Phillips X-ray diffraction unit and Ni filtered Cu K radiation.

RESULTS AND DISCUSSION

The analyses of the soils and the associated mottles are presented in Table 1. It is seen that the sulphur and iron content of the yellow mottles ranged from 30 to 40 per cent SO_3 , 35.7 to 42.9 per cent Fe_2O_3 , and the content of the whole soil from 6.5 to 9.8 per cent SO_3 and 5.9 to 9.3 per cent Fe_2O_3 . The silica, alumina, and organic matter content of the mottles, on the other hand, was lower than that of the soil. The yellow mottles would appear to have resulted from the accumulation of inorganic compounds of iron and sulphur on the surface of the peds and in old root channels. Since the mottles were shown to contain sulphur, the remainder of this work was aimed at determining the forms in which the sulphur was present.

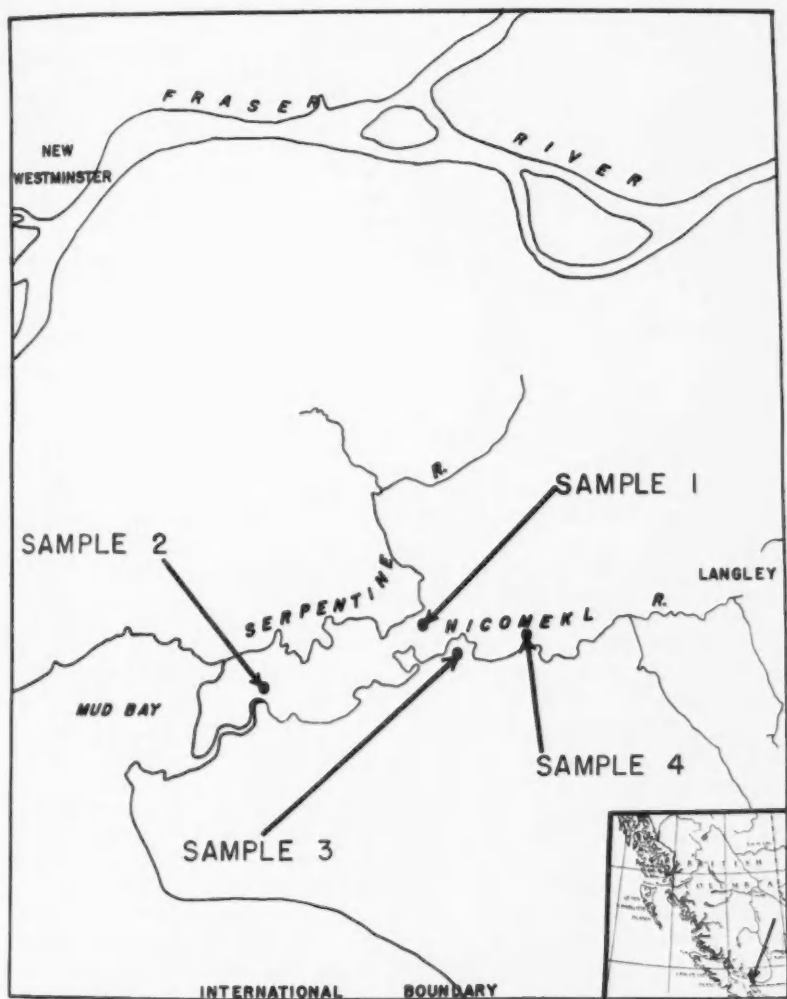


FIGURE 3. Map showing location of sampling sites.

Owing to the similarity of the analyses of the yellow mottle samples and the difficulty encountered in obtaining sufficient amounts of sample for analysis, all further chemical studies were made with samples from profile No. 2.

The total oxidizable sulphur content of the mottle sample was found to be 8.06 per cent SO_2 . No H_2S or other oxidizable gases were liberated by boiling the mottles in 1:1 HCl so no monosulphides, sulphites or thio-

TABLE 1. — CHEMICAL COMPOSITION OF YELLOW MOTTLES, BROWN TUBES AND ASSOCIATED SOILS¹

Sample	pH	Fe ₂ O ₃ %	SO ₃ %	SiO ₂ %	Al ₂ O ₃ %	CaO %	H ₂ O (110°C.) %	O.M. %	Con- ductivity mmhos. /cm.
1 Soil	3.50	9.30	9.84	51.23	9.92			9.66	2.1
1 A Yellow Mottles		42.9	40.00	19.32	3.78	4.04	3.22	2.07	
2 Soil	3.55	5.87	6.49	57.94	8.50			4.83	4.5
2 A Yellow Mottles		35.74	30.03	26.41	4.72	4.23	3.51	2.59	
3 Soil	3.25	6.44	7.02	57.60	10.87			2.42	1.6
3 A Yellow Mottles		37.40	35.30	25.22	4.00	4.04	3.76	1.38	
4 Soil	3.56	5.08	3.99	58.43	10.29			8.97	1.5
4 A Brown Tubes		15.21	10.90	51.83	10.14	6.05	23.10	3.62	

¹Analyses expressed as per cent of air dry weight

sulphates were present. No free sulphur was detected either by extraction with carbon disulphide or by the direct colorimetric method employing Schoenberg's reagent (12). In view of the low organic matter content of the mottles and the wide C:S ratio of soil organic materials (16), the organic sulphur content of the mottles would be low particularly in comparison to the total oxidizable sulphur content of 8.06 per cent SO₃. The total oxidizable sulphur of the mottles would, therefore, be made up largely of pyrites and other polysulphidic forms of the element. The greater part of the sulphur in the mottles was in the form of sulphate.

A sample of the yellow mottle was extracted with water but only a trace of sulphate was present in the aqueous extract. The yellow material was then boiled in 2 N HCl for 2 hours and the acid soluble iron and sulphate amounted to 28.61 per cent Fe₂O₃ and 19.26 per cent SO₃. Sulphate and iron were also present in the digestate from the monosulphidic sulphur determination. The low sulphide content and the liberation of iron and sulphate by dilute HCl, but not with water, would indicate that the yellow mottles were composed primarily of a basic ferric sulphate (10, 21).

As a further means of determining the nature of the compounds present in the mottles they were subjected to X-ray diffraction analysis. The "d spacing" values obtained before and after heating in 2 N HCl are given in Table 2. The other yellow mottles had virtually identical X-ray patterns. With the untreated mottle sample it is seen that lines attributable to quartz, illite (mica), chlorite, kaolinite, plagioclase feldspar, and amphiboles were evident along with intense lines at 3.07, 3.12 and 5.08 Å. These values, along with some less intense reflections at 3.67, 1.96, and 1.83 Å, agree closely with the values reported on A.S.T.M. Card No. 10-443 for jarosite, K Fe₃(SO₄)₂(OH)₂, and card No. 10-444 for carphosiderite, Fe₃(SO₄)₂(OH)₂(H₂O). It is also noted that many of these lines were eliminated or reduced in intensity after the mottles were digested in 2 N HCl. The sodium and potassium content of the 2 N HCl extract was 1.75 per cent K₂O

TABLE 2. — X-RAY DIFFRACTION DATA FOR YELLOW MOTTLES SAMPLE NO. 2 AND BROWN TUBE SAMPLE NO. 4

Sample No. 2 Yellow mottles No treatment		Sample No. 2 Yellow mottles Boiled in 2 N HCl		Sample No. 4 Brown tubes No treatment		Compound
<i>d A</i>	<i>I</i>	<i>d A</i>	<i>I</i>	<i>d A</i>	<i>I</i>	
10.04	0.5	10.01	0.2	10.06	0.15	Illite (mica) Amphiboles Chlorite, Kaolinite
		8.38	0.2	8.38	0.15	
7.16	0.3			7.15	0.1	
		6.23	0.2			
5.99	0.2			5.99	0.1	
5.72	0.3					
5.08	0.6	5.04	0.1	5.03	0.1	Illite (mica) Quartz
4.26	0.25	4.26	0.25	4.26	0.2	
3.67	0.2					
3.53	0.2	3.52	0.1			Chlorite, Kaolinite Quartz
3.35	0.7	3.36	1.0	3.35	1.0	
3.33	0.4					Illite (mica) Plag. feldspar
3.20	0.4	3.20	0.4	3.18	0.25	
3.12	0.85					
3.07	1.00					
2.98	0.1	2.89	0.1			
2.54	0.3					
		2.49	0.15	2.50	0.15	
2.27	0.3	2.31	0.15	2.27	0.1	Quartz Illite (mica)
2.02	0.2	2.00	0.10	2.01	0.15	
1.96	0.4					
1.83	0.4	1.83	0.25	1.83	0.2	Quartz
1.55	0.1	1.55	0.1	1.52	0.1	Quartz
1.38	0.3	1.38	0.15			

and 1.16 per cent Na_2O so that it is possible that both jarosite and natrojarosite were present. Even if all the potassium and sodium extracted with acid were present as jarosite and natrojarosite their content was not sufficient to account for all the sulphate extracted. It is possible that the remaining sulphate in the mottles was in the form of carphosiderite.

An estimate of the composition of the mottles can be made by assuming that the sulphate extracted with 2 N HCl was present as jarosite (18.6 per cent $\text{K Fe}_3(\text{SO}_4)_2(\text{OH})_6$), natrojarosite (18.3 per cent $\text{Na Fe}_3(\text{SO}_4)_2(\text{OH})_6$), and carphosiderite (22.3 per cent $\text{H}_2\text{O} \cdot \text{Fe}_3(\text{SO}_4)_2(\text{OH})_6 \cdot \text{H}_2\text{O}$) and that the remaining sulphur was in the form of pyrites (8.0 per cent FeS_2). These values, along with the analyses obtained for SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , H_2O (110°C.) and organic matter, result in a total of analysis of 110 per cent. The reason for this high value is not clear. Moss (11) has shown that carphosiderite does not exist so that the sulphate in excess of that present as the jarosites may have been present as a less basic sulphate than carphosiderite and which was not detected by X-ray analysis. If 8.0 per cent crystalline pyrite were present it probably would have been evident in the X-ray analysis also. It is probable that the so-called pyrites was in reality a complex polysulphide of iron and present in an amorphous state. Too, the value obtained for oxidizable sulphur by digestion of the mottles in acid

containing tin was lower than the difference between the total sulphur and the acid-soluble sulphate, so that it would appear that all the oxidizable sulphur in the mottles was not recovered by this procedure. Although the exact chemical composition of the mottles cannot be determined without further study of the procedures for separating the various forms of sulphur, it is evident from this work that the mottles were composed mainly of jarosites along with pyrites or other polysulphides of iron and that these were mixed with other soil components such as quartz and mica.

It is seen from Table 1 that the brown tubes contained less sulphur and iron than the yellow mottles. More sulphur and iron was present in the brown tubes than in the soil matrix but the silica and organic matter content was lower. The polysulphidic sulphur content was found to be 7.16 per cent SO_2 . Quartz, illite (mica), chlorite, kaolinite, feldspar and amphiboles were detected by X-ray analysis (Table 2). The brown tubes appear to be formed of soil particles cemented together by iron sulphides, sulphates and possibly oxides produced in the vicinity of roots.

The mottles and brown tubes used in this study were obtained from soils lying close to the tidal Nicomekl and Serpentine Rivers, the waters of which contain considerable amounts of salts including sulphates. Seepage of this water into the soil and perhaps occasional flooding of the low-lying areas would introduce sulphate and other salts into these soils and result in the relatively high conductivities recorded in Table 1. It is possible that some of these deltaic deposits were laid down in the sea so that sulphur was introduced into the soil in this way. The occurrence of yellow mottles in the Lower Fraser Valley only in soils adjacent to tidal rivers or the sea would suggest that seepage of sea-water is necessary to maintain the yellow mottle and tubular formations in this coastal area. The work on polder and some reclaimed soils would indicate that the sulphate is first reduced to sulphide giving rise to the formation of pyrites (4, 7, 22, 23). According to some workers, oxidation of the pyrites may take place with the formation of a ferric sulphate (3, 4, 7, 22) but it has also been reported that pyrite is oxidized to $\text{Fe}(\text{OH})_3$ and free S (4, 15). The poorly drained, brackish conditions encountered in these acid organic soils of the Lower Fraser Valley provide conditions ideally suited to the reduction of sulphates to form pyrites which were oxidized subsequently to a basic ferric sulphate.

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APPENDIX

Profile No. 1. Shallow Organic

<i>Horizon</i>	<i>Depth (in.)</i>	<i>Description</i>
Ha	18-12	Very dark grey (10YR3/1 dry) and black (10YR2/1 moist); well decomposed muck; weak fine granular structure; loose dry but very friable moist.
FH1	12-6	Very dark greyish brown (10YR3/2 dry) and very dark brown (10YR2/2 moist); mucky peat. A compacted horizon.
FH2	6-0	Very dark greyish brown (10YR3/2 dry) and very dark brown (10YR2/2 moist); mucky peat; granular structure; slightly compact dry friable moist. Old plant roots and plant remains abundant. Yellow mottling starts at the lower 2 inches of this horizon.
Cg1	0-6	Dark greyish brown (10YR4/2 moist); silt loam. Horizon stained by organic matter leached from above. In this horizon yellow mottling is most prominent. It is found in matrix usually around some old plant remains.
Cg2	6" +	Olive grey (5Y4/2 moist); massive silt loam. Many partially decomposed roots and plant remains. Yellow mottling in upper 4 inches but not very pronounced. Brown mottling abundant at 7 inches.

Profile No. 2. Orthic Gleysol

<i>Horizon</i>	<i>Depth (in.)</i>	<i>Description</i>
Aa	0-7	Pale brown (10YR6/3 dry) and dark greyish brown (10YR4/2 moist). Silt loam; weak medium to coarse blocky structure; slightly hard dry and friable moist. Many fine roots.
Cg1	7-18	Light grey (5YR6/1 dry) and dark grey (10YR4/1 moist). Stratified silt loam with few yellowish brown to pale yellow mottles. Slightly hard dry and friable moist. Many roots in upper part, thinning to only a few in the lower part.
Cg2	18-36	Light grey to grey (10YR6/1 dry) and dark grey (10YR4/1 moist). Stratified silt loam matrix with distinct yellow mottles especially around root channels and old plant remains. Yellow mottling forms coating on matrix and in some places the yellow coat is covered by a reddish brown coat of organic matter. Massive, but with cracks 3 to 5 inches wide extending through this horizon. In these cracks, the yellow coating is of high chroma. Here too, there is a coating of organic matter over the yellow mottling.
Cg3	36" +	Light grey to grey (10YR6/1 dry) and dark grey (10YR4/1 moist). Stratified silt loam matrix with faint yellowish brown to pale yellow mottles in the upper 6 inches. No roots except in cracks.

Profile No. 3. Peaty Gleysol

<i>Horizon</i>	<i>Depth (in.)</i>	<i>Description</i>
Ha	12-6	Dark grey to very dark grey (10YR3.5/1 dry) and black (10YR.2/1 moist) muck; weak fine to medium granular structure in upper part and weak coarse subangular blocky in lower part; soft dry, very friable moist. Many fine roots.
FH	6-0	Partially to well decomposed mucky peat that is black in the upper portion and brownish in the lower. Horizon is compacted and very hard when dry. Numerous fine roots in upper part thinning rapidly to only a few in the lower part.
Cg1	0-15	Light olive grey (5YR6/2 dry) and grey (5Y5/1 moist). Silt loam matrix with prominent yellow mottling and yellow and yellowish brown tubes especially around old roots and other plant remains. There are also a few dark reddish brown mottles.
Cg2	15" +	Light grey to grey (10YR6/1 dry) and dark grey (10YR4/1 moist). Silt loam with few distinct dark yellowish brown and dark reddish brown mottles confined to old root channels and other plant remains. Massive; friable moist; non-sticky but slightly plastic wet. Plant remains abundant in upper 8 inches.

Profile No. 4. Shallow Organic

<i>Horizon</i>	<i>Depth (in.)</i>	<i>Description</i>
Ha	15-8	Same as horizon 1 in Profile No. 1.
FH	8-0	Same as horizon 2 in Profile No. 1.
Cg1	0-9	Same as horizon 4 in Profile No. 1, except that no yellow mottlings are present; however, brown mottling is intense. Brown tubular material is found abundantly in matrix usually around some old plant remains.
Cg2	9" +	Same as horizon 5 in Profile No. 1, except that yellow mottlings are absent.

MINERALOGICAL COMPOSITION OF SOME GREY WOODED SOILS DEVELOPED FROM GLACIAL TILL¹

S. PAWLUK²

University of Alberta, Edmonton, Alberta

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ABSTRACT

Grey Wooded profiles representing five soil series developed on glacial till in Alberta were studied. The clay mineral fraction in these soils was found to contain montmorillonite, illite, kaolinite and quartz. Authigenic chlorite and "mixed layer" structures were present in the soil sola. Examination of the fine sand fraction revealed the presence of quartz, potash-feldspars and soda-calcic feldspars in the light (sp. gr. < 2.70) mineral fraction with biotite, muscovite, chlorite and highly weathered amphiboles and pyroxenes comprising the intermediate (sp. gr. 2.70-2.96) mineral fraction. The heavy (sp. gr. > 2.96) mineral fraction contained primarily iron oxides, amphiboles, garnets and pyroxenes with a wide variety of other minerals in relatively low quantities.

The mineralogical data presented suggest variations in weathering in the sola of the soils studied, despite their similar morphological features. Active and exchange acidity showed little relationship to the degree of mineral weathering. Weathering appeared to be more severe in horizons where acid conditions result from the presence of exchangeable hydrogen rather than where similar acid conditions result from exchangeable aluminium. The mineralogical study was found to be exceedingly valuable in distinguishing between morphologically similar materials of different lithology.

INTRODUCTION

The Grey Wooded soils reviewed in this study are developed on glacial till deposits derived from differing geological formations. The parent materials are generally somewhat calcareous but may be acidic. Although the profiles are similar in morphology, little is known about their mineralogical compositions and degree of mineral weathering. The objective of this study was, therefore, designed to assess the mineralogical status of the Grey Wooded soils in order to determine their similarities as well as to evaluate the degree of profile weathering.

The five soil series included in this study are developed in well to moderately well drained topographic positions and their profiles are considered to be "orthic" for the Grey Wooded Group. The L³ horizon is comprised principally of undecomposed leaves and twigs, the accumulation products from forest cover. The major tree species are aspen poplar *Populus tremuloides* sometimes intermixed with white spruce *Picea glauca*. A pronounced F layer is present, containing fungi mycelia intermixed with semi-decomposed organic material. The general absence of a well formed humus H horizon is characteristic and may be assumed to indicate that fairly rapid mineralization occurs in the F layer. The total depth of the organic layer seldom exceeds 2 to 3 inches. An Ae horizon with a friable consistency and exhibiting a platy structure is characteristic although it may vary from 2 to 6 inches in thickness. The Ae horizon is partly eluviated of both fine (less than 0.2 micron) and coarse (2 to 0.2 microns)

¹Contribution from the Soil Science Department, University of Alberta, Edmonton, Alta.

²Assistant Professor of Soil Science, University of Alberta.

³Horizon nomenclature is in accordance with that accepted by the National Soil Survey Committee of Canada, Guelph, Ont. 1960.

clays. The colour in the moist state varies from pale brown (10 YR 6/3)¹ to light yellowish brown (10 YR 6/4). Clay accumulation is the most important characteristic of the Bt horizon which has a fine to medium blocky structure and a firm consistency in the upper portion. The lower Bt horizon varies from brown (10 YR 5/3) in the upper portion to yellowish brown (10 YR 5/6) in the lower portion. Transitional layers AB and BC horizons may be present. The C horizons of the series included in the present study consist of till deposits.

Since the tills contain from 80 to 85 per cent local bedrock materials in their fabric² and have a decisive influence upon inherent soil profile characteristics the underlying geological formations are described.

The Braeburn soil profile (section 31-74-5-W6) was sampled in the southern portion of the Saddle Hills. The glacial material in this region is underlain by the basal and lower Wapiti beds (6,7). Lithologically the Wapiti formation consists of sandstones and shales of fresh-water deposition. The basal and lower Wapiti beds are predominantly argillaceous. Thin bands of clay iron-stone concretions are common. On the whole, fine-grained textures are prevalent. The lower part of the Wapiti formation is considered to be the stratigraphical equivalent of the Belly River formation.

The Alcan soil profile (section 36-84-16-W6) is formed from glacial tills derived in part from lower Smoky River shale (Kaskapau) of marine origin (3). This member of the Smoky group is generally thin bedded, dark to black in colour with occasional ironstone concretions. There are also some thin beds of fine grained sandstones present in the lower portion of the formation. The materials are high in pyrite (FeS₂) which oxidizes when exposed near the surface to the oxide form of iron.

The Demmitt profile (section 35-74-13-W6) was sampled approximately 50 miles west of the Braeburn profile. The bedrock formation underlying the tills of this region is described as the middle to upper Wapiti formation. The upper portion of the formation is commonly found to be light grey to buff fine grained sandstone³.

The Cooking Lake profile (section 12-53-21-W4) was sampled in a region where the underlying bedrock formation is difficult to ascertain. The immediate underlying material appears to consist of the eastern extremes of lower continental beds of the Edmonton formation. Immediately to the east is the Belly River formation. It is, therefore, quite logical to assume that the composition of the local material in the till is to some extent an expression of the adjacent beds of the Belly River formation as well as the lower beds of the Edmonton formation. The lower Edmonton beds are largely comprised of interbedded non-marine, bentonitic, light-coloured sandstone and grey and brown shales. Iron bands and ironstone concretions are common (4). The most abundant rock type in the Belly River formation is a mixture of sand and clay in variable proportions with a characteristic rock-type of light grey massive sandstone (9).

¹Munsell designations.

²Bayrock, L. A. Research Council of Alberta, Edmonton, Alta. Unpublished data.

³Ground Water Section, Earth Science Division, Research Council of Alberta, Edmonton, Alta.

TABLE 1.—CLAY MINERAL DISTRIBUTION IN GREY WOODED SOILS OF ALBERTA

Soil series and horizon	Montmorillonite		Illite		Kaolinite		Chlorite		Mixed layers		Quartz		C.E.C. ¹	
	2-0.2 microns	<0.2 microns	2-0.2 microns	<0.2 microns	2-0.2 microns	<0.2 microns	2-0.2 microns	<0.2 microns	2-0.2 microns	<0.2 microns	2-0.2 microns	<0.2 microns	2-0.2 microns	<0.2 microns
Braeburn	2 ²	5 ²	4 ²	2 ²	3-4 ³	2 ²	1 ³	1 ²	3 ²	3 ²	3-4 ²	2 ²	20.2	65.2
	3	5	4	2	3-4	2	2	1	1	3	3	2	19.1	76.2
	3	5	4	2	3-4	2	1	1	1	3	3	2	23.4	68.9
Breton	2	5	4	2-3	3	2	3	1	2	3	3	2	17.6	63.3
	3	5	4	2-3	3	2-3	3	1	3-4	3	3	2	18.3	70.1
	3	5	4	2	3	2	2	1	2	3	3	2	23.7	69.0
Demmitt	1	4	4	2-3	3-4	3	2	1	3-4	3	3-4	2	18.9	69.8
	3	5	3-4	2	3-4	2	2	1	3	1	3	2	18.4	78.5
	3	5	4	2	3-4	2	2	1	3-2	1	3	2	24.6	77.1
Cooking Lake	3-4	5	4	2-3	3	2	1	1	2	1	3	2	26.2	69.8
	1	4	3-4	2	3	2-3	3-4	2	4-5	2-3	3	2	23.2	65.8
	3	4	4	3	3	3	3-4	1-2	3-4	3	3	2	19.5	73.4
Alkan	3	4	4	3	3	2-3	2	1	2	1	3	2	25.1	70.0
	1	5	3-4	2	3	2-3	3	1	3-4	1	3	2	23.2	59.4
	1	5	4	2	3	3	3	1	2	1	3	2	23.8	60.9
	2	2	4	3-4	3	3	2	1	3	3-4	3	2	23.4	41.8

¹Milliequivalent per 100 grams
²Expressed as relative quantities in the following serial progression:

1. None
2. Trace
3. Minor
4. Major
5. Dominant

0 — 10%
 10 — 35%
 35 — 65%
 65 — 100%

The Breton profile (section 6-48-3-W5) is formed from till underlain by the basal Paskapoo beds characterized by massive, crossbedded sandstones. This formation is of fresh-water deposition. The sandstone outcrops within a relatively short distance of the sampling site. Water-well logs have shown that the thickness of the sandstone in the Breton area exceeds 60 feet in depth.

METHODS OF ANALYSES

The samples which were collected in 1958 were passed through a 2-millimetre sieve and fractionated for mineralogical studies. Fractionation was carried out by sedimentation techniques. The sand fraction was removed by sieving methods. The clay and silt fractions were then treated with dilute acid (0.1 N HCl) in order to remove all carbonates. The excess cations in the soil solution were removed by repeated washing and centrifuging. The clays were then brought into a 1.5 per cent suspension with water and adjusted to pH 8.0 with dilute NaOH. Separations into a 2 to 0.2 micron and less than 0.2 micron fractions were done by centrifuge.

Specific gravity separations of the very fine sand fraction were carried out by heavy liquid techniques. X-ray analyses were conducted on oriented clays mounted on glass slides using a Norelco high angle geiger counter X-ray diffractometer.

Semi-quantitative estimates for clay mineral distribution were based upon cation exchange data, comparisons with standard X-ray diffraction patterns determined for Alberta clay minerals of known composition, comparison of peak intensities as discussed by Weaver (8) as well as accumulated information from previous unpublished research data incorporating fusion analyses.

RESULTS AND DISCUSSION OF RESULTS

X-ray Analyses of Clays

Results for X-ray analyses, cation exchange capacities and distribution percentage for the two clay fractions are reported in Tables 1 and 2.

Montmorillonite is, in general, the major clay mineral component of the inorganic colloidal fraction in the B and C soil horizons. An exception is the C₂ horizon of the Alcan profile where montmorillonite is almost absent in both the fine and coarse clay fractions. The fine clay fraction in all other samples is largely montmorillonite. Varying amounts occur in the coarse clay fractions. The coarse clay fractions of the Ae horizons contain only trace quantities of montmorillonite. The lower portions of the sola have somewhat higher amounts.

X-ray analyses conducted on fine clay fractions saturated with various exchangeable cations strongly suggest the presence of a montmorillonite clay mineral in the upper part of the sola that differs somewhat in its "d" spacing from the montmorillonite present in the parent material. The montmorillonite that appears to form *in situ* exhibits less expansion upon glycolation (15.5-16A°) than does the allogenic mineral (17.0A°) inherent to the till parent material. This feature is best expressed in the solum of the Cooking

TABLE 2. — SOME ANALYTICAL CHARACTERISTICS OF GREY WOODED SOILS

Profile and horizon		Depth (inches)	pH	Exchange acidity % of C.E.C.	Clay %	
					2.0-0.2 (microns)	0.2 (micron)
Braeburn	LF	2-0	5.8	16.0	—	—
	Ae	0-3	6.0	16.9	7	1
	AB	3-5	5.3	16.5	16	5
	Bt ₁	5-8	5.1	18.3	19	11
	Bt ₂	8-16	4.9	18.9	17	16
	BC	16-21	4.8	18.6	19	18
	BC ₂	21-41	5.0	11.6	20	16
	Ck	41+	7.4	—	21	12
Breton	LF	1-0	6.4	7.1	—	—
	Ae	0-5	5.3	37.4	11	5
	AB	5-10	5.3	21.4	17	16
	Bt ₁	10-16	5.0	20.3	21	20
	Bt ₂	16-26	4.9	19.5	19	22
	BC	26-37	5.1	12.7	13	14
	C	37+	7.0	0.0	15	9
Demmitt	LF	1-0	6.2	12.8	—	—
	Ae ₁	0-4	6.3	23.9	5	2
	Ae ₂	4-9	5.9	19.4	9	3
	Bt ₁	9-13	5.4	10.8	17	18
	Bt ₂	13-21	5.3	12.2	24	16
	BC	21-37	5.5	3.4	18	16
	C	37+	7.0	1.4	24	8
Cooking Lake	LF	3-0	6.4	7.1	—	—
	Ae	0-5	6.1	15.4	12	3
	Bt	5-11	4.8	11.9	21	16
	BC	11-24	4.2	13.7	17	17
	C ₁	24-29	7.1	0.0	21	13
	C ₂	29+	7.5	—	19	12
Alcan	Ahe	0-1	6.6	16.7	9	0
	Ae	1-4	4.8	48.2	10	0
	AB	4-7	4.5	54.2	19	8
	BA	7-10	4.4	49.8	22	20
	Bt	10-24	4.1	45.0	22	21
	BC	24-31	4.4	38.9	18	20
	C ₁	31-40	4.6	34.4	19	11
	C ₂	40+	7.3	0.0	30	20

Lake profile. Similar results were reported previously for the Cooking Lake soils (1).

Illite is, in general, the major clay mineral component of the coarse clay fraction. It is found in only relatively low quantities in the fine clay fraction. An exception is the Alcan series where it occurs in somewhat larger amounts.

Kaolinite occurs in minor to trace quantities in the Grey Wooded soils included in this study. The relative content of kaolinite in the coarse clay fraction is generally minor while only minor to trace amounts are found in the fine clay fraction.

Characteristics of the 14\AA "d" spacings are indicative of chlorite minerals present in varying amounts in the coarse clay fractions in the upper portions of the sola of these Grey Wooded soils. It has been reasonably well established that these chlorite minerals are closely associated with "mixed-layer" structures and the montmorillonite formed *in situ* in a weathering sequence between illite and montmorillonite. The nature and mechanism of this transformation have been discussed elsewhere¹. The transformations are best expressed in the Cooking Lake profile and are of less significance in the remainder of the profiles.

"Mixed Layer" clay minerals are present in all profiles examined. However, their "d" spacings are not all similar. All profiles and horizons with exception of the Alcan C₆ have "mixed layer" clay minerals which exhibit "d" spacings between 10\AA to 14\AA and 14\AA to 16\AA . These minerals have their maximum content in the coarse clay fractions of the Ae horizons and their minimum content in the C horizons. The mixed layering present is characterized by X-ray patterns similar to those previously reported for interstratification of illite-chlorite-montmorillonite (8). However, its presence in the upper sola in quantities much greater than in the parent materials as well as its close association with the chlorite mineral suggest an authigenic origin.

The presence of "mixed layer" minerals in the C₆ horizon of the Alcan profile was established from a series of low peaks on a plateau between 10\AA and 14\AA which appeared on the X-ray patterns of the glycolated samples. The spacings collapsed to a sharp 10\AA peak after heating to 550°C . The mixed layer structure appeared to be an interstratification of illite and montmorillonite and inherent to the parent material. The origin of these minerals may be attributed to marine environments (8).

Fine grain quartz generally occurs in minor amounts in the coarse clay fraction and only in traces in the fine clay fraction of all samples.

Total cation exchange capacities determined for the two clay fractions are also reported in Table 1. The cation exchange capacities reflect the composition of the two clay fractions. The low exchange capacity of the coarse clay fraction is an indication of the high illite content as well as the presence of kaolinite. High exchange capacities for the fine clay fractions reflect the large content of montmorillonite present. The lower exchange capacity for the fine clay of the C₆ horizons of the Alcan profile as compared to the remaining profiles verify the X-ray data which show little or no montmorillonite and a high content of illite-montmorillonite "mixed layering".

Chemical Analyses

The analytical data reported in Tables 2 and 3 were selected for this study in order to assist in evaluating the mineralogical status of the soils. The pH determinations show the sola of the Grey Wooded soils studied

¹Pawluk, S. Characteristics of Grey Wooded soils developed from glacial till deposits of the Peace River and north central regions of Alberta. Presented to the 7th Intern. Congress of Soil Sci., Madison, Wis. 1960.

TABLE 3. — EXTRACTABLE OXIDES IN SOME GREY WOODED SOILS

	Soil series and horizon	Fe ₂ O ₃ %	SiO ₂ %	Al ₂ O ₃ %
Braeburn	Ae	0.33	.166	0.22
	Bt	2.40	.188	0.30
	C ₁	1.05	.352	0.00
Breton	Ae	0.54	.186	0.42
	Bt	1.38	.322	0.50
	C ₁	1.05	.386	0.20
Demmitt	Ae ₁	0.36	.170	0.26
	Ae ₂	0.72	.116	0.30
	Bt	1.32	.110	0.54
	C ₁	0.84	.362	0.08
Cooking Lake	Ae	0.39	.302	0.08
	Bt	1.32	.286	0.38
	C ₂	0.66	.314	0.08
Alcan	Ae	1.05	.384	0.66
	Bt	1.74	.368	0.58
	C ₂	1.62	.312	0.26

to be, in general, mildly acid. However, the BC horizons of the Cooking Lake series, and the B horizon of the Alcan series, approach severely acid soil conditions. The Alcan solum appears to have developed from a parent material with inherent acidity and is distinctly different from the underlying slightly alkaline C₂ material. The exchange acidity present in the majority of horizons is relatively low and only occupies a major portion of the exchange positions in the Alcan solum. Analyses reported elsewhere⁷ have shown that a major amount of the exchange acidity in the upper sola and the entire amount in the lower sola of all profiles studied may be attributed to exchangeable aluminum present on the exchange complex.

The data for clay mineral distribution indicate that almost all clay transpositions within the soil sola involve the size fraction less than 0.2 micron. There is also strong evidence supporting the fact that the coarse clay in the Ae breaks down to the fine clay size prior to or during transposition.

Easily extractable hydrous oxides in soil profiles usually result from dissolution of inorganic soil mineral constituents and reflect in part the degree of chemical weathering which has taken place. Extractable hydrous iron oxide as illustrated in the data of Table 3 is composed of the oxides soluble in hot sodium hydrosulphite solution. Its maximum accumulation is evident in the B horizons. Data in Table 3 indicate that extractable silica measured by its solubility in hot sodium carbonate solution, attains its maximum concentration in the C horizons. Extractable alumina consists of both exchangeable aluminium and weak-alkali-soluble hydrous aluminium oxides. Although total content is not high it does appear to accumulate in the B horizons.

⁷Pawluk. op. cit., p. 7.

TABLE 4. — COMPOSITION AND MOLECULAR RATIOS OF THE 0.10-0.15 SAND FRACTION (sp. gr. less than 2.70)

Soil series and horizons	Quartz %	K-feldspar %	Soda-calcic feldspar %	Molecular ratios			
				$\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}$	$\frac{\text{SiO}_2}{\text{CaO}}$	$\frac{\text{SiO}_2}{\text{Na}_2\text{O}}$	$\frac{\text{SiO}_2}{\text{K}_2\text{O}}$
Braeburn Ae	83	5	12	23.1	426	88	156
Bt	82	6	12	21.9	470	81	151
C ₁	81	6	13	20.7	382	73	146
Breton Ae	69	9	22	17.4	105	59	94
Bt	68	9	23	16.5	105	55	90
C ₁	61	11	28	12.6	82	43	72
Demmitt Ae ₁	76	6	17	15.7	144	75	136
Ae ₂	67	7	26	9.4	78	50	109
Bt	63	8	29	8.2	71	41	97
C ₁	61	8	31	7.1	59	40	94
Cooking Lake Ae	83	5	12	12.9	281	86	154
Bt	73	7	20	9.2	143	53	114
C ₂	60	8	32	7.8	54	41	92
Alcan Ae	90	5	5	30.1	875	211	186
Bt	88	6	6	29.7	731	196	143
C ₂	95		2	35.9	2227	554	318

Light Mineral Analyses

The composition and molecular ratios for the 0.10 to the 0.15 millimetre sand fraction having a specific gravity less than 2.70 are given in Table 4. The data were computed from X-ray and total fusion analyses. The X-ray diffractometer analyses show quartz, potassium feldspar and soda-calcic feldspar to be the minerals present in the sand fraction under study. Among the various soda-calcic feldspars, the content of anorthite appears relatively low with the major portion of these minerals ranging from labradorite to albite. The Breton, Demmitt, and Cooking Lake profiles are similar in their feldspar distribution in the parent materials while the Braeburn and Alcan profiles have lesser quantities. The very low content of feldspars in the C₂ horizon of the Alcan as compared to that for the solum suggests that the material in this horizon is of different origin. The molecular ratios reflect the amount of weathering which has occurred in the soil sola. All profiles exhibit variable degrees of dissolution of feldspars ranging from relatively slight in the Braeburn to fairly severe in the Cooking Lake profile.

Heavy Mineral Composition of the 0.10 to 0.15 mm. Sand Fraction (sp. gr. > 2.96)

Data for heavy mineral composition of the Grey Wooded profiles included in this study are presented in Table 5.

TABLE 5.—HEAVY MINERAL COMPOSITION OF SOME GREY WOODED SOILS

Minerals	Breton			Braeburn			Cooking Lake			Dennitt			Alcan			
	Ae	Bt	C	Ae	Bt	C	Ae	Bt	C ₂	Ae ₁	Ae ₂	Bt	C	Ae	Bt	C ₂
Magnetite	10 ¹	9	11	12	11	23	15	15	30	18	17	21	18	5	8	3
Hematite and limonite	33	34	28	17	33	8	41	48	33	15	12	21	12	50	53	87
Total Fe oxides	43	44	39	29	44	31	56	63	63	33	29	41	30	55	61	90
Amphiboles	24	19	21	37	25	25	8	7	6	22	31	22	27	10	15	4
Garnets	9	14	15	13	10	22	12	14	8	21	21	15	22	15	9	<1
Pyroxenes (monoclinic)	1	2	3	1	1	3	2	1	1	3	1	2	1	2	2	—
Pyroxenes (orthorhombic)	4	4	3	3	2	1	2	2	2	3	3	2	4	2	2	<1
Apatite	—	—	4	—	1	6	2	3	5	—	—	6	4	2	1	—
Zircon	—	1	1	1	2	1	2	1	3	3	2	1	2	—	—	—
Epidote (inc. altered)	9	5	5	6	5	3	3	1	1	8	2	3	4	3	3	1
Tourmaline	1	1	2	2	3	2	1	<1	1	3	3	2	3	4	1	—
Chlorite and chloritoid	—	—	—	—	—	—	2	1	1	—	—	—	—	—	—	—
Leucosine	—	2	1	1	3	1	3	3	3	—	2	—	1	1	—	1
Minerals altered to white	4	2	1	3	3	2	5	2	2	1	1	<1	1	1	1	<1
Miscellaneous*	1	3	4	2	—	1	1	<1	2	2	4	2	—	4	4	2
Unidentified	1	2	1	2	1	2	1	<1	2	1	1	1	<1	1	1	1

¹Based on percentage. Standard deviation for all values is 1% based on a count of 300 mineral grains.

*Biotite, serpentine, staurolite, titanite, sillimanite, gold, rutile kyanite, glauconite, beryl, cassiterite, monazite. Present in insignificant quantities.

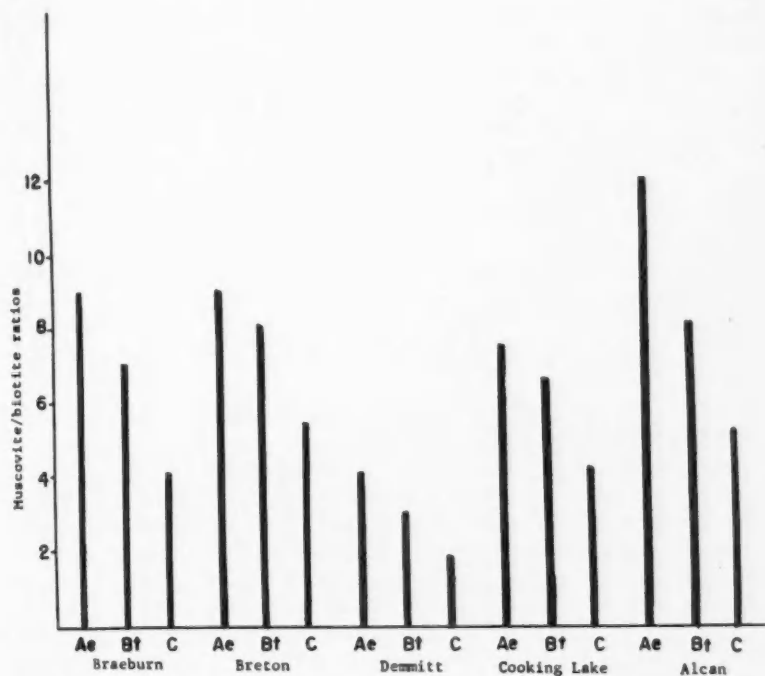


FIGURE 1. Comparison of the muscovite/biotite ratios of major horizons from five Grey Wooded soils.

Among the various mineral species identified, only the iron oxides and apatite show any trends for variation in the various horizons of these profiles. Alteration of magnetite to hematite and limonite appears evident in the Breton, Braeburn and Cooking Lake profiles with a slight build up of limonite and hematite in the B horizons. Apatite appears to be severely weathered in all profiles. The extremely high quantity of iron oxides and the low content of the silicate minerals for the C₂ horizon material of the Alcan profile as compared to the solum further suggest a different origin for these materials.

The value of heavy mineral counts as a means of assessing soil profile development in glacial parent materials which are found in Alberta¹ is questionable on account of the variability in the heavy mineral distribution over relatively short distances established by statistical computations for 300 grain counts.

¹Bayrock, L. A. Heavy minerals in tills of Alberta. Research Council of Alberta, Edmonton, Alta. Unpublished data.

*Intermediate Mineral Composition of the 0.10 to 0.15 mm. Sand Fraction
(sp. gr. 2.70-2.96)*

The mineralogical composition of the intermediate fraction (sp. gr. 2.70 to 2.96) consists of largely muscovite, biotite, chlorite, as well as considerable portions of strongly weathered amphiboles and pyroxenes.

Muscovite shows little evidence of weathering in the soils while the biotite is much less stable (Figure 1). The green variety of biotite is least stable and almost completely removed by weathering processes active in the soil sola.

The pyroxenes and amphiboles present in the fraction exhibit white weathering coatings on the surfaces. Even after cleaning with sodium hydrosulphite solution prominent coatings remained. The coatings rendered the major portion of the mineral surfaces opaque and extremely difficult to identify.

Pebble Counts for the Till Parent Materials

The results of pebble counts for the five parent materials are given in Table 6. Since the mineralogical status of the Alcan solum was drastically different from the C₂ horizon, pebble counts were conducted on the upper 48 inches, separate from the lower 48 inches.

The composition of pebbles found in glacial till reflect in part the source area for the material. High quantities of igneous and metamorphic pebbles suggest that the pebbles have been largely transported by ice from the Canadian Shield, while high quantities of pebbles of Cretaceous origin suggest local bedrock sources for the materials. Ratios calculated for quartzites vs. igneous and metamorphic rocks fall well within the established

TABLE 6.—PEBBLE COUNTS FOR PARENT MATERIALS OF SOME GREY WOODED SOILS

	Brae- burn series	Breton series	Dem- mitt series	Cooking Lake series	Alcan	
					Upper 48 in.	Below 48 in.
<i>Pebbles</i>						
Igneous and metamorphic	93	108	25	102	87	41
Quartzite	112	143	28	120	68	28
Upper Cretaceous						
(1) Iron concretions	79	11	9	21	50	86
(2) Phyllites						
cherts						
sandstones	16	38	238	42	93	145
siltstones						
slates						
Dolomitic	—	—	—	15	2	—
<i>Ratios</i>						
Quartzite vs.						
igneous and metamorphic	1.20	1.32	1.12	1.18	0.78	0.68
Igneous and metamorphic vs. Upper Cretaceous	0.98	2.25	0.10	1.62	0.61	0.18

range for till of Keewatin (eastern) origin¹. Ratios calculated for igneous and metamorphic vs. Upper Cretaceous rocks generally reflect the content of local bedrock material within the till deposit. The data in Table 6 suggest that the Braeburn, Breton, and Cooking Lake profiles as well as the solum of the Alcan have lesser quantities of local bedrock than have the Demmitt profile and the Alcan C₂ horizon. For example the Breton profile is underlain by soft Paskapoo sandstone; however the quantity of sandstone pebbles present in the parent material at the sampling site is relatively low.

The variation in pebble composition between the upper and basal tills of the Alcan profile is so great as to suggest a clear cut distinction between the two materials. The till deposits probably reflect two lithologically different bedrock formations. It appears that the composition of tills may vary greatly over extremely short distances depending upon a complexity of factors related to ice mechanics and variabilities in bedrock erodability.

Acidity of Soils and Mineralogical Weathering

The mineralogical data presented show variations in the rate of weathering in the sola of the soils studied. Although morphological features of all profiles are very similar the Cooking Lake profile appears to be the most weathered. Despite the high acidity and low base saturation, there is little evidence of severe weathering in the Alcan solum.

A comparison of both active and exchange acidity with the degree of weathering present in the profiles shows little relationship and suggests that the most severe weathering need not necessarily occur in the most acidic horizons. Apparently minerals are much more stable under acid conditions resulting from the presence of exchangeable alumina than where hydrogen ions contribute to the exchange acidity. For example the Ae horizons which are frequently leached by acidic decomposition products of the forest litter are generally more highly weathered than the lower sola despite their relatively higher pH and exchangeable base saturation.

The foregoing discussion also suggests that pH and exchangeable acidity should be largely discounted in differentiating between Grey Wooded and Podzol soils. It appears that the degree of acidity cannot always influence pedogenic processes to such an extent as to prohibit the formation of Grey Wooded soils on acid parent materials, as commonly believed to be the case (2). The Alcan upper till (C₁ horizon), for example, has high acidity and low base saturation; however, there is no indication of Podzol soil formation in the solum. The acidity of the material may be attributed to exchangeable aluminium which appears as an inherent feature.

CONCLUSIONS

Based on data presented and the foregoing discussion, the following conclusions appear warranted:

1. The analytical data establish these Grey Wooded soils as being pedogenically separable from Podzol soils. Some points of evidence for this fact are: low content of translocated sesquioxides, lack of severe chemical weathering of minerals, enrichment of clay minerals in the B horizons.

¹Earth Science Branch, Research Council of Alberta, Edmonton, Alta. *Personal communication.*

2. The soil profiles reviewed in this study are separable on both their genetic and inherent mineralogical characteristics. Variability in degree of weathering and the composition of upper cretaceous pebbles in the parent materials reflecting local bedrock composition appear most indicative. However, before series separations are justified on these bases, variations among profiles within mappable series must be further tested on a statistical basis.
3. Mineralogical studies are of importance in obtaining a better understanding of soil pedogenic processes and soil classification. This is especially true where anomalies in physical and chemical data are evident in morphologically similar profiles.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance provided by the Earth Science Division of the Research Council of Alberta throughout this study. Further acknowledgement is extended to members of the Alberta Soil Survey, members of the Soil Science Department, and C. F. Bentley, Dean of Agriculture, University of Alberta, for helpful suggestions in reviewing the manuscript.

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USE OF SOIL CORES IN SOIL CLASSIFICATION¹

J. A. TOOGOOD²
University of Alberta, Edmonton, Alberta

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ABSTRACT

The value of soil cores in soil classification was examined by a statistical study of the physical properties of five soil types, using 3 x 3-inch soil cores. Analyses of variance when five replicates were used showed that field capacity differences of about 5 per cent could be detected throughout the solum of these soils. Distinctions in volume weight and total porosity were readily made, significance differences ($P = 0.95$) being about 0.1 gram per cubic centimetre and 4 per cent respectively. Tension plate measurements were precise enough to show significant differences between some of the soils in the Ah horizon but between none in the Bt horizon. Hydraulic conductivity measurements seemed to be of little value as no differences in the five soils could be demonstrated statistically. The results obtained indicate that routine tests of this kind by soil surveyors would yield some useful information and assist in the classification of soils.

INTRODUCTION

A previous paper (1) presented data showing the extent of variation in a number of physical properties of fine and medium textured soils from which cores were collected with a Uhland sampler. Cores taken measured 3 x 3 inches. It was concluded that five replicates would give sufficient accuracy for measuring field capacity and volume weight but more replicates would be required for determining non-capillary and total porosity and still more for permeability measurements.

Five soil types in the Edmonton area were selected to test the value of the procedure in differentiating soil types on the basis of the physical properties measured. The object was to compare a number of soils, which surveyors had already classified as to type, and examine their physical properties. Would soil cores show significant differences? Would soil cores have been of value in the original classification of these soils?

MATERIALS AND METHODS

Five soil types, previously classified by the Alberta Soil Survey, and differing in parent material, soil sub-group, and texture were selected for the study. All samples were taken from virgin profiles. The soils are described briefly in Table 1. Profiles were wetted artificially and core

¹Contribution from Department of Soil Science, University of Alberta, Edmonton, Alta.

²Professor of Soil Science, University of Alberta, Edmonton, Alta.

TABLE 1. — DESCRIPTION OF SOIL TYPES INCLUDED IN THIS STUDY

Type	Parent material	Sub-group	Symbol in Figure 1
Angus Ridge loam	Till	Eluviated Black	Ar.L
Camrose loam	Till	Black Solodized Solonetz	Cam.L
Malmo silty clay loam	Lacustrine	Black Solod	Mo.SiCL
Ponoka loam	Alluvial-lacustrine	Orthic Black	Pk.L
Peace Hills sandy loam	Alluvial-aeolian	Orthic Black	Ph.SL

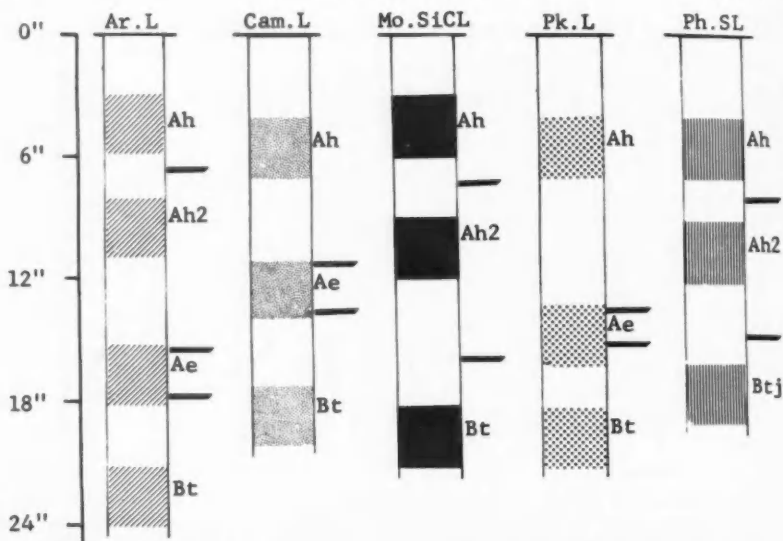


FIGURE 1. Location of core samples with respect to depth in inches relative to the various horizons in the five soil types. The hatching used above is repeated in the following figures to designate the soil type.

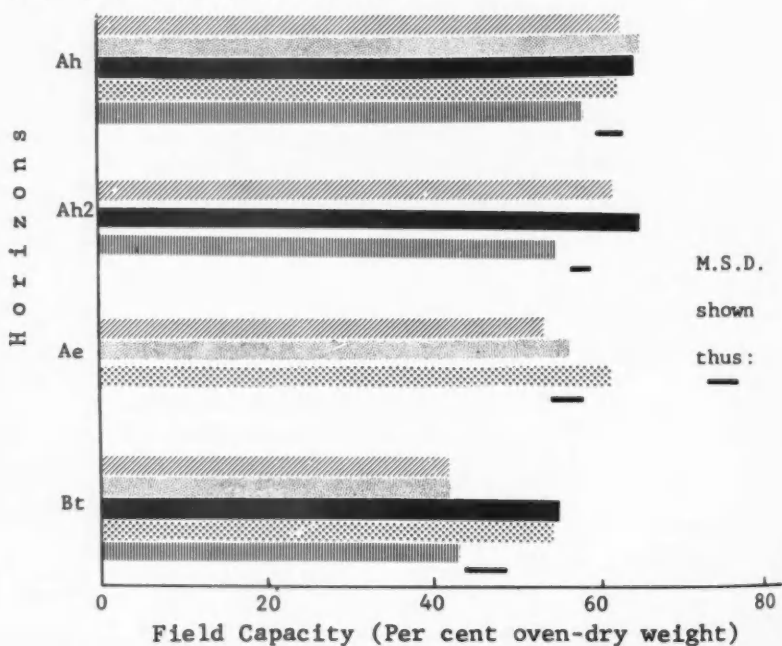


FIGURE 2. Field capacity data for the five soil types. See Figure 1 for key to cross-hatching of bars. Each bar in this and following figures is average for five cores.

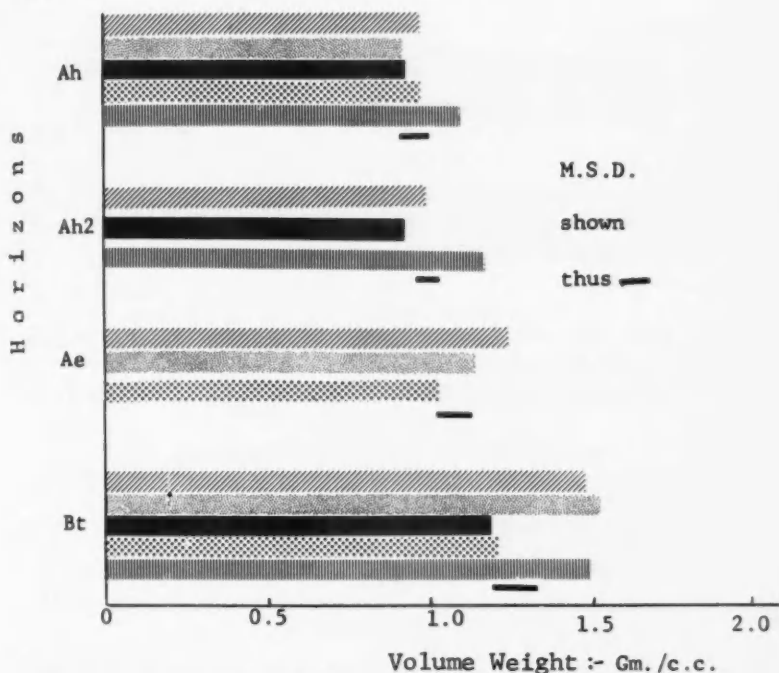


FIGURE 3. Volume weight data for the five soil types. See Figure 1 for key to cross-hatching of bars.

samples taken 48 hours later from Ah, Ah2, Ae (where present) and Bt horizons, five replicates being taken in each case. The horizon designations used replace A_{11} , A_{12} , A_s and B_s respectively, the nomenclature used in Canada before 1960. The symbol Ah used in this paper may also be read as Ah1. Maximum depth of sampling was 24 inches. Methods used in the physical analyses were those described by Uhland and O'Neal (2) for measuring field capacity, volume weight, total porosity, 60-centimetre porosity and hydraulic conductivity.

RESULTS AND DISCUSSION

Results of the investigation are shown graphically in Figures 1 to 6. Minimum significant differences at the 5 per cent level are shown for the laboratory tests for each horizon. The figures illustrate variations within the profile for each soil type, variations between similar horizons of different soil types, and the degree of success of the method in showing on the basis of five replicates, significant differences between similar horizons of different soil types. It is the latter point which is of greatest interest to the soil surveyor.

While it is true the five soil types cover only a limited range of textures and parent materials, the following conclusions appear to be justified:

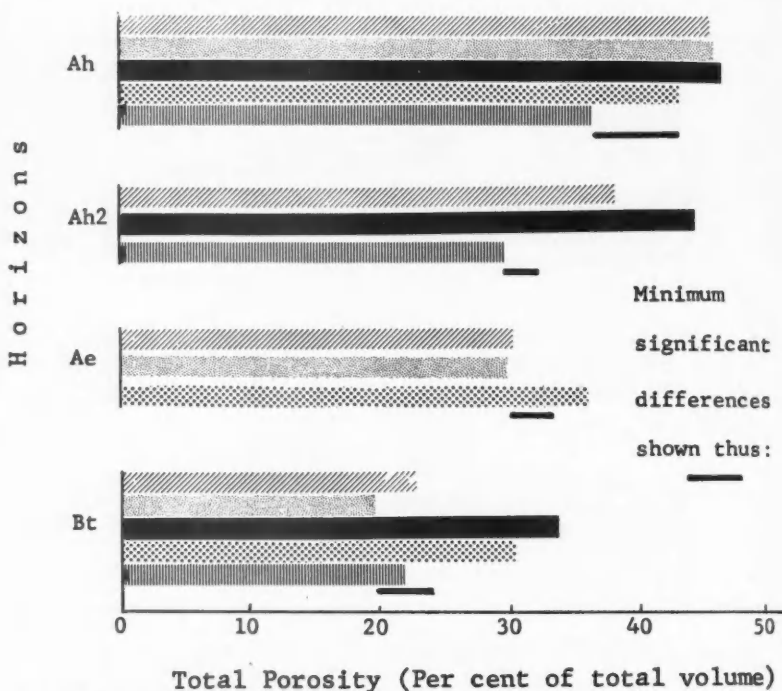


FIGURE 4. Total porosity data for the five soil types. See Figure 1 for key to cross-hatching of bars.

1. Field capacity differences of Ah horizons when measured statistically are not easily detected as those of Ah2 horizons (see Figure 2). Below the Ah2 horizons variability between cores increases with depth but in general it appears that differences of about 5 per cent can be detected with this technique. Significant differences of less than 3 per cent are not detectable with only five cores. An error in technique is indicated by the field capacity measured for the Camrose loam Bt cores. The average should have been about 5 per cent higher. It is suggested that the low value was a consequence of failure of the water added to infiltrate to the 18-inch depth in the 48-hour period allowed.
2. Volume weights for A and B horizons are easily determined using soil cores, and significant differences of about 0.1 gram per cubic centimetre can be detected with five replications (see Figure 3). As expected the fine-textured Malmo soil shows a significantly lower volume weight than the coarse-textured Peace Hills soil, with the loam soils intermediate.
3. Significant differences in total porosity of about 4 per cent are fairly easily detected in all horizons except Ah. The Bt cores varied more than the Ah2 or Ae, a fact reflected by the larger minimum significant

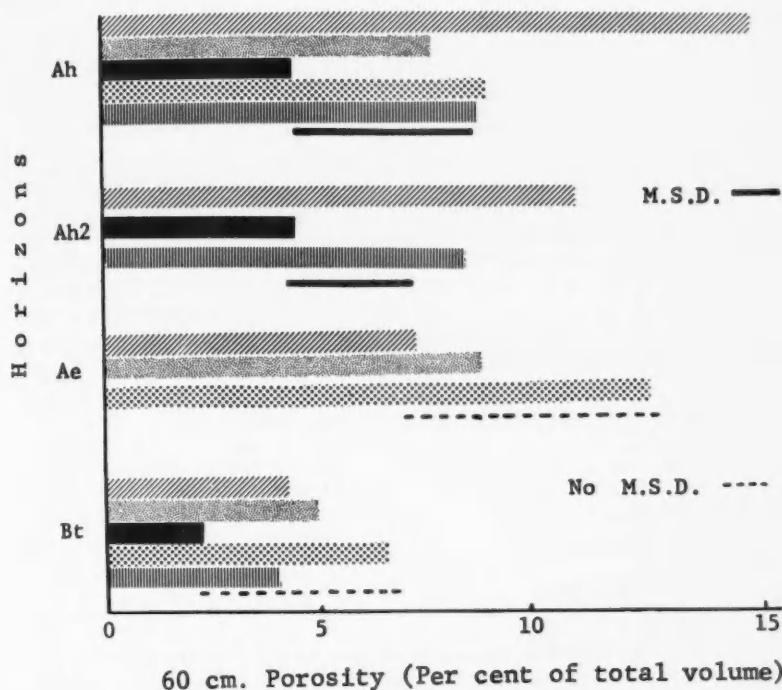


FIGURE 5. Data for porosity at 60-cm. tension for the five soil types. See Figure 1 for key to cross-hatching of bars.

difference. If distinctions are to be made between soils differing by less than 4 per cent, it is likely that more than five replicates would be needed.

4. Wide variations occur in measurement of 60-centimetre porosity, whether comparing replicates, horizons, or soil types. With only five replicates, significant differences are revealed only with the Ah and Ah2 cores.
5. Variation in values for hydraulic conductivity are so great that no significant differences can be detected when only five replicates are used.
6. It would appear that in the classification of soils, it is relatively easy to demonstrate more differences in physical characteristics than are at present being published in most Canadian soil survey reports. The ease of demonstrating significant differences between certain horizons and soil types with respect to some physical properties justifies more extensive use of soil cores. It is true that more time is required in the field for sampling than for samples taken for chemical analysis but this disadvantage is offset by the shorter time required in the laboratory to complete the determinations. Data for field capacity, volume weight

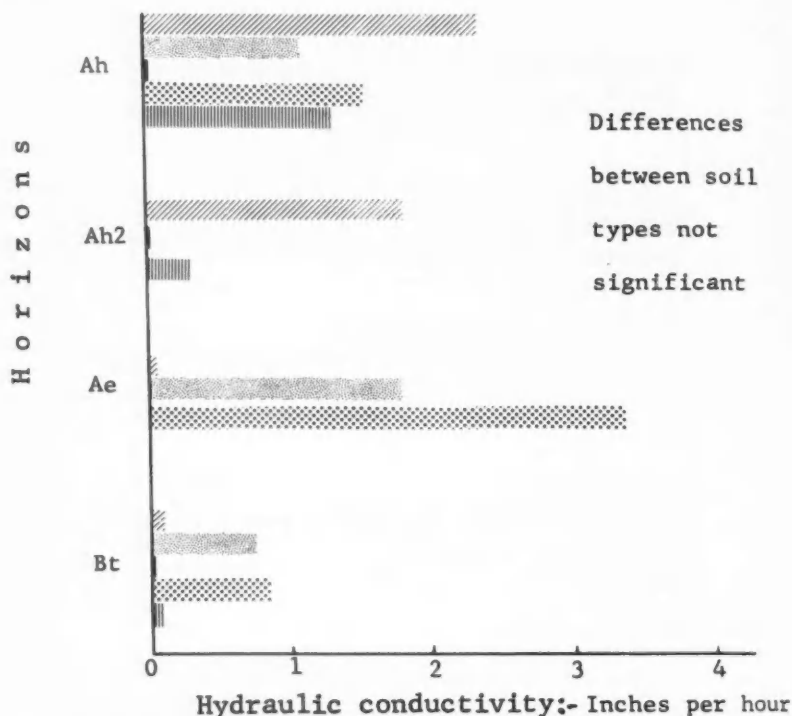


FIGURE 6. Hydraulic conductivity data for the five soil types. See Figure 1 for key to cross-hatching of bars.

and total porosity, especially, are worthy of attention in the routine analysis of soil survey samples. Hydraulic conductivity and 60-centimetre porosity, however, do not appear to be measured accurately enough to merit inclusion as routine procedure.

ACKNOWLEDGEMENT

Financial assistance from the National Research Council is gratefully acknowledged.

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NOTE ON THE RELATION OF SOIL BULK DENSITY TO THE INCIDENCE OF PHYTOPHTHORA ROOT AND STALK ROT OF SOYBEANS¹

Extensive field observations indicated that the incidence of root and stalk rot of soybeans caused by *Phytophthora megasperma* var. *sojae* was markedly and consistently more severe on fine-textured soils subjected to shallow tillage or concentrated implement traffic. A severe outbreak of the disease was induced by shallow tillage of a field of Brookston clay loam in which three preceding stands of a susceptible variety of soybeans, planted after the soil had been ploughed, were free from the disease. Surface soil from this field was taken to the greenhouse, placed in glazed crocks, treated as indicated in Table 1, and planted to the susceptible soybean variety, Harosoy. Incidence of the disease as related to treatment of the soil is shown in Table 1.

TABLE 1.—THE RELATION OF BULK DENSITY AND MOISTURE REGIME
TO THE INCIDENCE OF PHYTOPHTHORA-INFECTED PLANTS

Bulk density		Incidence of infected plants ¹	
0-4 in. gm./cc.	4-8 in. gm./cc.	Low moisture tension per cent	High moisture tension per cent
1.20	1.20	2.5	2.5
1.20	1.49	3.8	5.0
1.49	1.20	8.8	21.3
1.49	1.49	35.1	45.0

¹Average of four replications

The outstanding feature of the experiment was the high incidence of infected plants occurring when all the soil in the crock was compacted, a circumstance which reflected the strong interaction of surface x subsurface compaction. Surface and subsurface compaction separately had relatively little effect on incidence of the disease. Although three of the four comparisons presented show an increase in the average number of infected plants at the high moisture tension, these differences as well as the interactions between moisture and density were statistically non-significant. Various aspects of this problem are being studied further.

—J. M. FULTON,
—C. G. MORTIMORE,
—A. A. HILDEBRAND,
Research Station,
Canada Department of Agriculture,
Harrow, Ontario

April 12, 1961

¹Contribution No. 24, Research Station, Research Branch, Canada Department of Agriculture, Harrow, Ont.

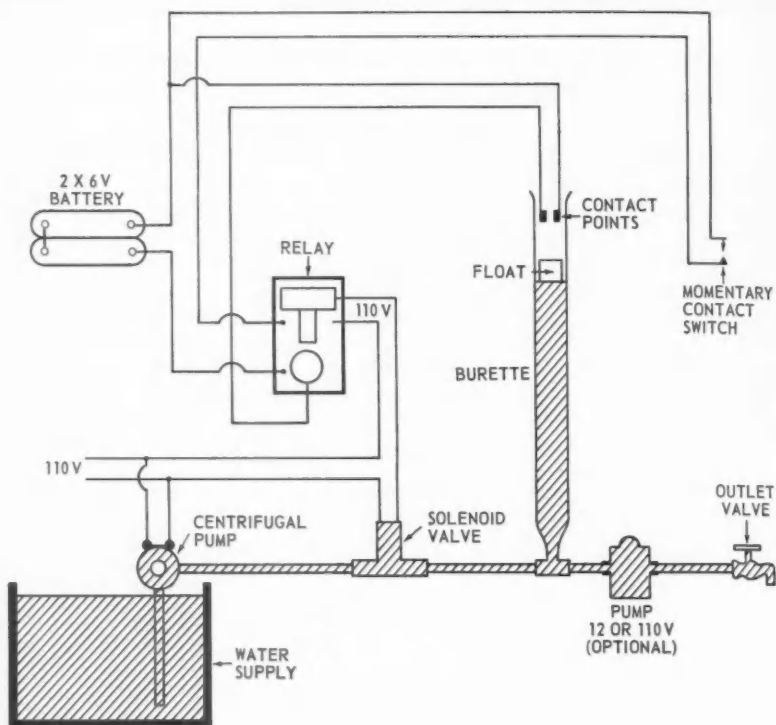


FIGURE 1. Schematic diagram of the dispenser.

NOTE ON A SEMI-AUTOMATIC DISPENSER FOR WATER IN THE GREENHOUSE¹

An apparatus is described for dispensing measured volumes of non-ionic liquids. The equipment was designed specifically to facilitate watering plants in the greenhouse where different amounts of water are to be applied. It could also be used for dispensing nutrient solutions in the greenhouse or growth rooms.

A schematic diagram of the apparatus as used in the greenhouse for de-ionized water is presented in Figure 1. The metering system employs a burette of sufficient size for the maximum amount of water required for any pot. The refill system is activated manually by a momentary-electrical switch, conveniently located near the hand-operated outlet valve. Upon contact by the switch, activating the relay, the solenoid valve opens allowing water to enter the burette. The float, contacting the points in the filled burette, automatically closes the solenoid valve. The equipment may be attached directly to a central water supply or to a centrifugal pump for additional pressure on the inlet line. A second pump may be included in

¹Contribution No. 25, Soil Research Institute, Research Branch, Canada Department of Agriculture, Ottawa, Ont.

the outlet line if the flow by gravity is not sufficient. The second pump may be either a 12-V autopulse type or a small 110-V centrifugal type. Discharge of the dispensed volume is controlled by a hand-operated outlet valve attached to flexible tubing.

The apparatus is placed on a small movable cart to facilitate recording data and watering the plants. In actual operation the hinged lid of the cart may be lowered to support the operator's records.

For an electrically conducting solution, the float could be deleted without affecting the basic principles of operation.

Details on the model and source of supply of the component parts may be obtained from the authors.

—ALEX R. MACK,
—R. BRUCE SANDERSON,
Soil Research Institute,
Canada Department of Agriculture,
Ottawa, Canada

March 29, 1961

NOTE ON EFFECTS OF WETTING AND DRYING ON READINGS OF ELECTRICAL RESISTANCE BLOCKS IN SOIL¹

Soil moisture electrical resistance blocks have been found (8) to have different resistances when drying than when wetting. This hysteresis effect is, however, of little practical importance in irrigated soil, where resistance readings are usually made during the drying part of the cycle only.

Of greater importance is the fact that, with continued use of the blocks, their resistance readings at any one moisture content in the drying part of the cycle have been reported to change with time. Such changes have been attributed to various causes such as a change in the block itself (9), a change in salinity (5, 7) or successive wettings and dryings (3). Bouyoucos (2) reported rapid deterioration of uncoated gypsum blocks in saturated soils.

Cannell (3) grew oats in cans of soil in a growth chamber, determined the soil moisture contents by weighing the cans, and measured the resistances of several kinds of blocks placed at mid-depth in the soil. The first irrigation cycle was started about the time of planting. During the last cycle the resistance values were significantly higher ($P = .001$) than those at the same moisture contents during the first cycle.

Field studies made at Summerland, B.C., have indicated no marked change in block readings even after several years of use. Accordingly, a test similar to that of Cannell was made in a growth chamber. One can was filled with a loamy sand, one with a sandy loam, one with a silt loam, and one with a clay loam. The pH varied from 7.2 to 7.7, there was no lime present, and the electrical conductivity was low, ranging from 0.9 to 1.3 mhos $\times 10^6$. A Bouyoucos gypsum block (2) was placed in the bottom centre of each can, and the following blocks were placed at mid-depth:

- 2 Bouyoucos gypsum blocks (2)
- 2 Bouyoucos nylon blocks (1)
- 1 Youker fibreglas-gypsum block (10)
- 1 Colman fibreglas block (4).

Each container was planted to ladino clover. The soil was wetted to above field capacity, then as frequently as needed until the experiment was started. Readings were taken periodically on the blocks, and as soon as the bottom blocks showed approximately the same degree of drying as the blocks at mid-depth, the experiment was started. The next irrigation (Cycle 1) and every third irrigation thereafter was made using Hoagland's nutrient solution (6). The soil was allowed to dry to half the available moisture content, then re-wetted. This was continued for 12 irrigation cycles. At frequent intervals the cans were weighed and block resistances determined. The heavy crop of clover was clipped frequently to constant height.

¹Contribution No. 60, Research Station, Research Branch, Canada Department of Agriculture, Summerland, B.C.

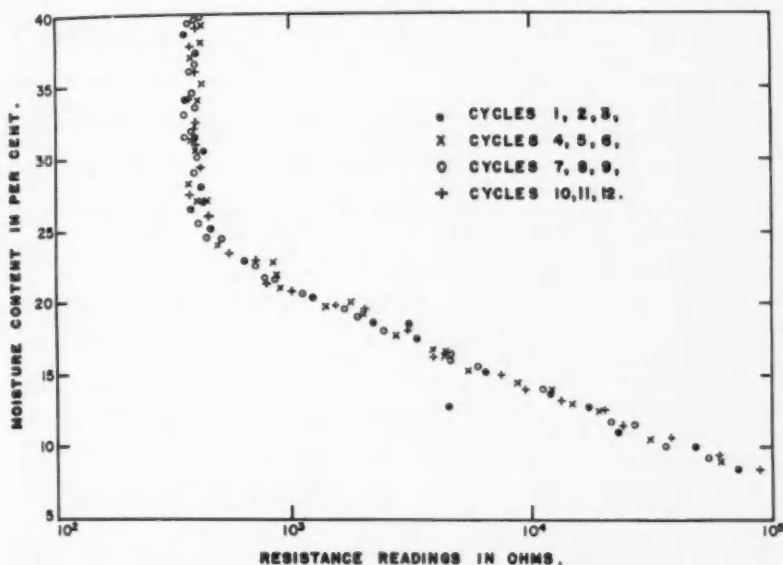


FIGURE 1. Moisture contents of a silt loam soil planted to ladino clover, plotted against resistance readings of Bouyoucos electric resistance blocks over a period of 12 drying cycles.

A chart of moisture contents plotted against resistance readings was made for each of the 24 mid-depth blocks. Not one of these charts showed any consistent change in block readings with successive wettings and dryings. As an example, Figure 1 shows the values for a Bouyoucos gypsum block in the silt loam soil. The readings of successive cycles were so close and so interwoven that statistical studies on curve differences did not appear justified.

At the end of the experiment the blocks and their leads were all examined carefully. No deterioration could be found in the Colman or nylon blocks. The gypsum blocks had lost 10.5 per cent of their weight, but were still firm and had clean electrodes.

The question arises as to why no change in block readings was found with successive wettings and dryings. The following two suggestions are offered: 1) Little if any deterioration occurred in the blocks. This may have been due to the moderately alkaline reaction and low salinity of the soil. 2) The experiment was not started until the soil was well permeated with roots. Prior to this time it could not safely be assumed that the average moisture content of the container represented the moisture content around the blocks.

These results indicate 1) that under certain conditions the block readings do not necessarily change with continued use, and 2) that, where the readings do change, this is quite possibly due to other factors than wetting and drying.

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— J. C. WILCOX,
Canada Department of Agriculture,
Summerland, British Columbia

February 6, 1961

NOTE ON THE VOLUME OF INFLUENCE OF A NEUTRON SURFACE MOISTURE PROBE¹

The neutron surface moisture probe, placed on the soil surface, can be used along with an electronic scaler to determine the volumetric moisture content of the underlying soil. According to the manufacturer the effective measurement depth varies between 16 inches for dry soil and 5 inches for wet soil. It is also recommended that a container at least 24 inches square and 16 inches deep be used for laboratory calibrations.

An experiment was done to determine more specifically the effect of the volumetric moisture content on the vertical and horizontal dimensions of the volume of influence of the probe.

The vertical dimension of the volume of influence was determined by the use of a 58- x 58- x 58-centimetre box which had plywood sides and a transite bottom. The box was suspended 1 metre above a concrete floor so that a 10-centimetre layer of wax could be placed in contact with the underside of the box. The first four readings were obtained by placing the probe inside on the bottom of the box and by taking duplicate 1-minute counts with and without the wax layer present. The duplicate readings were obtained by rotating the probe through an angle of 90 degrees. All probe counts were expressed as the ratio to the mean of six standard counts, with the probe placed on the paraffin standard supplied by the manufacturer. The ratios to the standard, with the probe placed on the bottom of the box, were 0.023 without and 0.99 with wax. The values 0.023 and 0.99 are the starting points of the "without wax" and the "with wax" curves respectively (see Figure 2A). Then 25 pounds of soil were added to the box. Duplicate soil samples were taken for gravimetric soil moisture determination, and the soil was spread in the box and compacted. The depth of soil was measured and duplicate probe readings were made with and without wax. Additional 25-pound increments of soil were added until further addition of soil did not result in a change in the reading. The volumetric moisture content of the soil was calculated from the total weight and volume of the soil used and the per cent moisture by weight. The experiment was done seven times on three soils: A Fox sand parent material at 5.0 and 15.2 per cent moisture; a Burford loam topsoil at 28.5, 38.6, and 43.1 per cent moisture; and a Haldimand clay topsoil at 19.6 and 34.0 per cent moisture by volume. The results for four moisture contents are plotted in Figure 2A. The vertical dimension of the volume of influence was defined as the minimum depth of soil at which the "without wax" readings were the same as the "with wax" readings. A dashed smooth curve has been drawn in Figure 2A to indicate the decrease of the depth of influence as the moisture content of the soil increased.

The horizontal dimension of the volume of influence was determined for each soil after completion of the determination of the vertical dimension. In this experiment, one of the sides of the box was removed, so that the 10-centimetre layer of wax could be placed against the exposed side of the

¹Model P21, Serial No. 85, manufactured by Nuclear Chicago Corp., Chicago, Ill.

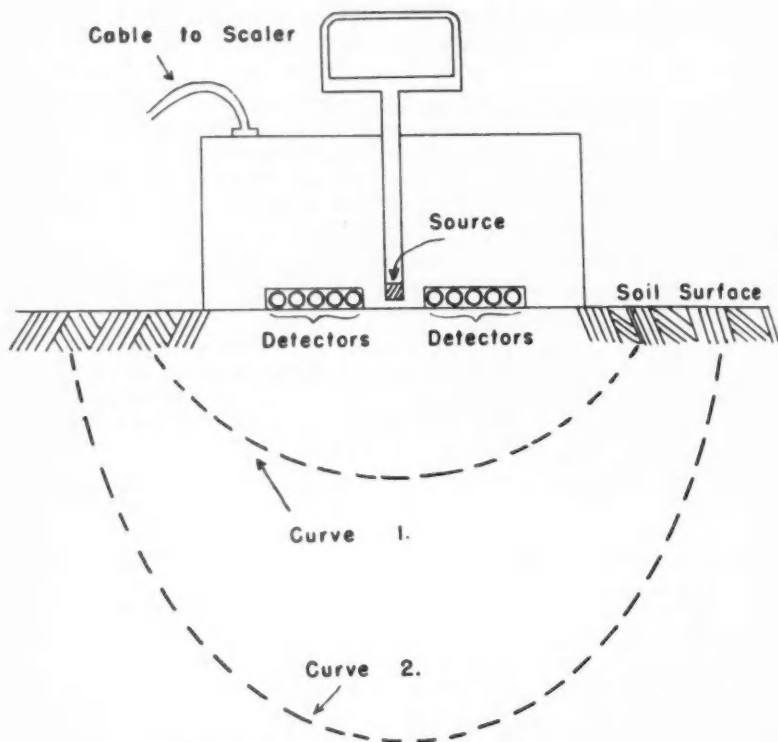


FIGURE 1. Cross-sectional view through the centre of the probe and the volumes of influence at two moisture contents; curve 1 at 43.1 per cent and curve 2 at 5.0 per cent moisture.

soil. The first four readings were obtained by placing the long edge of the probe flush with the edge of the soil and by taking duplicate counts with and without the wax present. Subsequent duplicate counts with and without wax were made at 2-centimetre intervals, moving the probe away from the edge of the soil. The duplicate counts were obtained by rotating the probe through an angle of 90 degrees; the orientation of the probe did not affect the probe readings. This procedure was continued till the probe was in the centre of the box. The horizontal dimension of the volume of influence was defined as twice the minimum distance between the fast neutron source and the edge of the soil at which the "without wax" readings were the same as the "with wax" readings. In Figure 2B, twice the distance between the fast neutron source and the edge of the soil is plotted versus the ratio of the count on the soil to that on the standard for the four different moisture contents. The higher ratio for each soil at the same distance

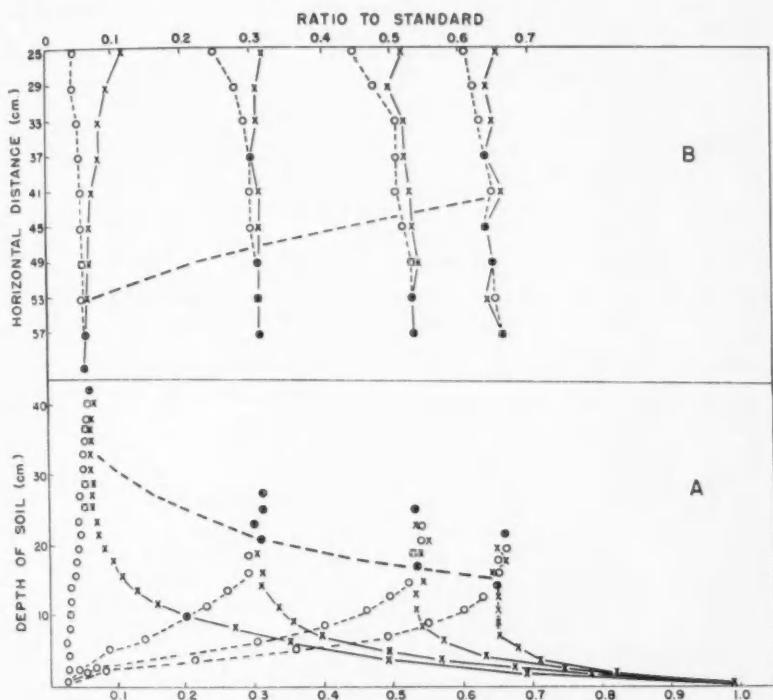


FIGURE 2. The variation of the probe count relative to the standard count with (A) change in soil depth and (B) twice the distance between the fast neutron source and the edge of the soil. The crosses (X) indicate the "with wax" and the open circles (O) indicate the "without wax" readings. From left to right the soils and their volumetric moisture percentages are: Fox sand parent material 5.0, Haldimand clay 19.6, Haldimand clay 34.0, Burford loam 43.1.

from the edge was obtained with the wax present. Although the horizontal dimension of the volume of influence seemed less definite than the depth of influence, a dashed smooth curve has been drawn to indicate the decrease in the horizontal dimension of the volume of influence with increased moisture content.

The vertical and horizontal dimensions of the volume of influence at the seven moisture contents are summarized in Table 1. In general, both the vertical and horizontal dimensions decrease with increasing soil moisture content, which is in agreement with the manufacturer's information. However, the vertical dimension of the volume of influence changes more rapidly (see Figure 1) than the horizontal dimension, and the shape changes with moisture content.

For actual field measurement the depth of influence is the most important characteristic. However, for laboratory calibration with soil in a

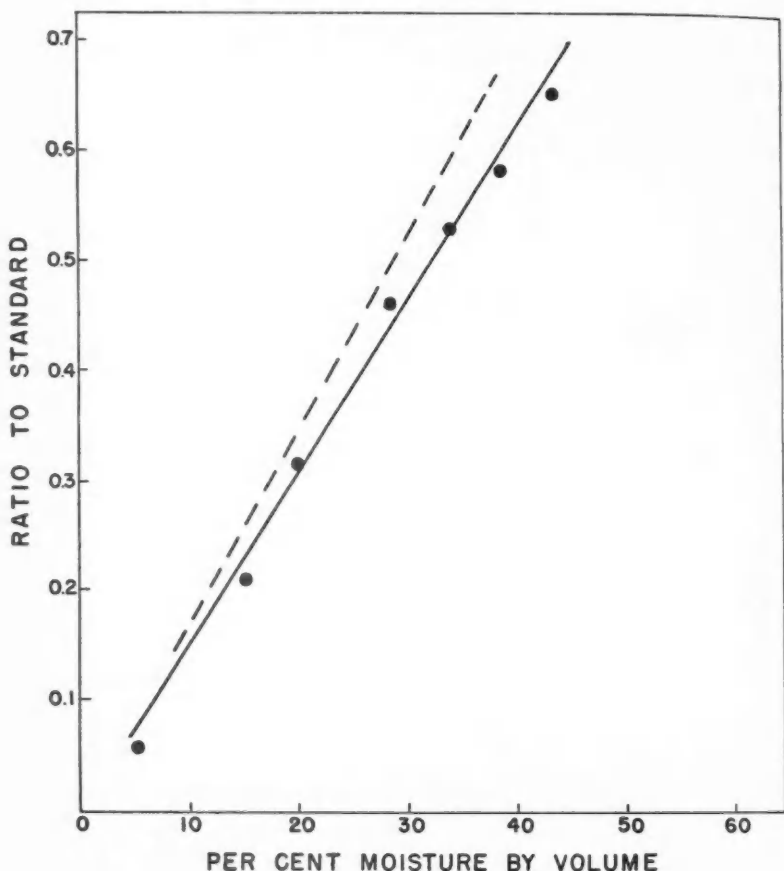


FIGURE 3. Calibration of the probe. The *solid* line is the line of best fit to the points determined in the experiment. The *broken* line is the manufacturer's calibration.

box, both the depth and the horizontal dimension, of the soil mass must be sufficiently large to prevent the escape of fast neutrons. From this experiment it is concluded that the size of the box recommended by the manufacturer is satisfactory for laboratory calibrations.

A calibration curve was prepared. In Figure 3 the plotted points are the actual determinations in this experiment, the solid line is the line of best fit, and the broken line is the calibration provided with the probe by the manufacturer. Since the agreement is unsatisfactory over the entire soil moisture range, it can be concluded that it is necessary to calibrate the probe before using it in the field.

TABLE 1.—THE VERTICAL AND HORIZONTAL DIMENSIONS OF THE VOLUME OF INFLUENCE AT DIFFERENT MOISTURE CONTENTS

Per cent moisture by volume		5.0	15.2	19.6	28.5	34.0	38.6	43.1
Dimensions of the volume of influence (cm.)	Vertical	34	24	21	17	16	15	14
	Horizontal	53	49	47	45	44	43	42

ACKNOWLEDGEMENT

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—J. DE VRIES,
 —K. M. KING,
 Department of Soil Science,
 Ontario Agricultural College,
 Guelph, Ontario

April 4, 1961

NOTE ON CALCULATING PER CENT MOISTURE WITH A DESK CALCULATOR

The desk calculator can be used for many purposes, one of which is the calculation of per cent moisture on a dry weight basis for soils, forages, and other materials. The method for calculating per cent moisture as outlined in this note can be used on most common models of desk calculators. It reduces the number of operations normally involved and eliminates the necessity of recording intermediate steps. We have found it to be faster than the method outlined by Marston (1) using negative numbers.

The procedure in the gravimetric method of determining moisture in a sample is: 1) weigh moist sample in a container of known weight, and 2) weigh the container with the sample when constant dry weight has been obtained. The difference in weight before and after drying is the weight of moisture that the sample contained. The final weight minus the weight of the container is the weight of the dry sample which, divided into the weight of the moisture, gives the per cent moisture in the sample on an oven-dry basis.

The conventional method of doing these calculations is to: 1) obtain the weight of moisture by subtraction and record this figure; 2) obtain the weight of dry sample and record this figure, and 3) divide the weight of the moisture by the weight of the dry sample to get the per cent moisture.

There is no need to record any figure except the per cent moisture when both sides of the keyboard of a desk calculator are used. As an example, let us use a case where the moist sample and container weigh 250.32 grams, the container and dry sample weigh 202.75 grams, and the container alone weighs 38.52 grams. The steps in calculating the per cent moisture and the set-up on a calculator capable of handling ten digits on the keyboard are:

1. Clear machine and centre the carriage.
2. On the left side of the keyboard place the weight of the container and wet sample, and on the right side of the keyboard the weight of the container and dry sample. Touch the plus (+) key to enter this on the carriage.

TABLE 1.—A METHOD OF CALCULATING PER CENT MOISTURE ON A DRY WEIGHT BASIS

Step no.	Machine appearance				Procedure
1	Carriage {	00000	00000	00000	Touch plus (+) key
	Keyboard {	25032	20275	00000	
2	Carriage {	00000	00001	00000	Touch minus (-) key
	Keyboard {	25032	20275	00000	
3	Carriage {	00000	03852	00000	Touch divide (÷) key
	Keyboard {	04757	16423	00000	
4	Carriage {	16423	00000	28.966	= % moisture
	Keyboard {	00000	00000	00000	
	Keyboard {	00000	00000	00000	

3. On the left side of the keyboard place the weight of the container and dry sample and on the right side place the weight of the container. Touch the minus (—) key. This gives the weight of the water on the left side of the carriage and the weight of the dry sample on the right.
4. Place the weight of the dry sample on the left side of the keyboard. Touch the divide (\div) key to obtain the answer.

This procedure is shown in Table 1. This will give the per cent moisture on a dry-weight basis correct to within 0.01. Leaving the weight of the dry sample on the right side of the carriage may affect the answer after the second decimal place. The answer to five decimal places is 28.96547 per cent. The procedure is the same on a machine that will handle eight numbers on the keyboard but is limited to four digit figures.

The procedure may be further shortened on certain models of machines. On at least one model, Step 1 can be eliminated by entering the figures on the keyboard as in Step 2 and pressing the "enter divide" key. Proceed with Steps 3 and 4 as outlined.

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—D. W. L. READ,
Canada Department of Agriculture,
Experimental Farm,
Swift Current, Saskatchewan

—R. J. REYNOLDS,
Directorate of Naval Ordnance,
Department of National Defence,
Ottawa, Ontario
(formerly at Swift Current Experimental Farm)

January 12, 1961

A NOTE ON AN AID FOR RAPID VACUUM FILTRATION

Analytical procedures for soil and plant material often require filtration by vacuum with a subsequent transfer of the filtrate to a beaker or volumetric flask for further treatment. Direct filtration into the beaker or flask is possible where the "Witt" filter jars, suggested by Peech (1), are employed. The glass "Witt" filter jars have not found widespread use, however, because they are only produced on special order, are subject to breakage, and require ground glass seals. This note describes a less expensive, relatively unbreakable and easily fabricated model.

The body of the jar (Figure 1) was constructed from a length of cast acrylic plastic tubing having a 3/8-inch wall thickness. A square base, which prevents tipping, was made from acrylic plastic sheet of the same thickness and sealed to the wall, using chloroform as an adhesive. The circular top of the same diameter as the wall was cut from half-inch acrylic plastic. A tapered hole was machined in the top to accept a No. 7 rubber stopper. The lower portion of the edge of the top was machined to fit inside the jar and to provide a lip to support the top on the wall. A slight groove was cut in that portion of the top which projects inside the jar to give a recess for a snug fit of a 3/16-inch thick, rubber "O" ring. The necessary vacuum seal, as low as 70 centimetres of mercury, was obtained by dampening the rubber ring and stopper with water. A serrated gas nozzle was threaded into the wall of the jar to provide a vacuum outlet. A series of jars attached to a manifold equipped with three-way stopcocks permit a number of samples to be rapidly filtered, and in addition, individual samples may be removed without losing the vacuum on the remaining samples.

Bubbling in the neck of a 100-millilitre volumetric flask and loss of a sample is avoided by use of a Tygon delivery tube to carry the sample below the neck of the volumetric flask. The spout of a glass Buchner funnel may be drawn down to fit the Tygon delivery tube. Further adaptations of the size of the unit to fit a variety of filtering requirements are possible.

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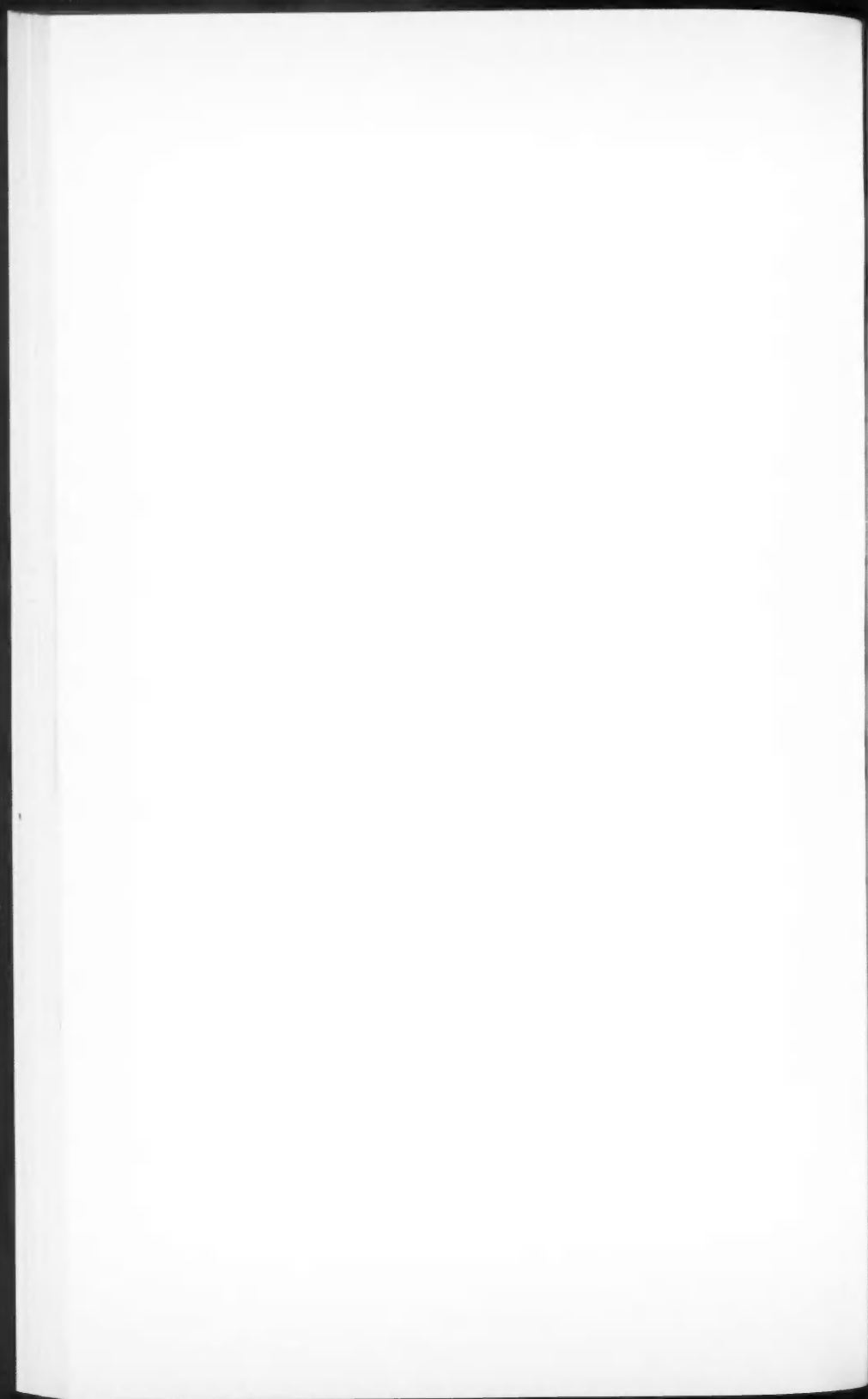
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—R. W. SHEARD,
Department of Soil Science,
Ontario Agricultural College,
Guelph, Ontario

May 15, 1961



FIGURE 1. A view of the filter jar assembly containing a 100-ml. volumetric flask.



Erratum:

In the February, 1961 (Vol. 41, No. 1) issue of the *Canadian Journal of Soil Science*, an article was published by S. Dubetz, entitled "Effect of soil type, soil moisture, and nitrogen fertilizer on the growth of spring wheat" (pp. 44-51).

We regret that errors occurred in the horizontal and vertical lines appearing in Tables 1 and 2. These tables have been corrected and appear on the following two pages; they should be substituted for the tables published on pages 46 and 48 of the February issue.

TABLE 1. — EFFECT OF THREE MOISTURE LEVELS ON SPRING WHEAT GROWN ON TWO SOILS (MEANS PER CROCK CALCULATED FROM FOUR REPLICATES AND FOUR NITROGEN LEVELS)

	Loam			Level of significance ¹	Loamy sand			Level of significance ¹	Mean		Level of significance ¹
	Moisture level				Moisture level				Loam	Loamy sand	
	¼	½	¾		¼	½	¾				
Height of wheat — inches	40	43	44	per cent 1	39	40	41	per cent 1	42	40	per cent 1
Number of heads	12	14	19	1	10	12	12	1	15	12	1
Weight of grain — grams	13.1	15.4	16.8	5	10.0	10.5	10.8	5	15.1	10.4	1
Weight of straw — grams	17	22	26	1	13	15	17	1	21	15	1
Weight of roots — grams	4	4	6	5	5	5	4	5	5	5	5
Protein in grain — per cent	12.9	11.2	10.4	5	10.9	10.6	10.7	5	11.5	11.1	1
Total protein — grams	1.69	1.73	1.73	5	1.07	1.09	1.13	5	1.72	1.10	1

¹Any two means underlined by the same line are not significantly different at the levels indicated

TABLE 2. — EFFECT OF FOUR LEVELS OF NITROGEN ON SPRING WHEAT GROWN ON TWO SOILS (MEANS PER CROCK CALCULATED FROM FOUR REPLICATES AND THREE MOISTURE LEVELS)

	Loam				Level of significance ¹	Loamy sand				Level of significance ¹
	lb. nitrogen per acre					lb. nitrogen per acre				
	0	30	60	90		0	30	60	90	
Height of wheat — inches	42	43	43	42	per cent 1	32	40	44	43	per cent 1
Number of heads	12	14	18	17	1	10	10	12	15	1
Weight of grain — grams	11.7	14.3	16.3	18.0	1	5.2	8.4	12.0	16.0	1
Weight of straw — grams	16	20	24	25	1	7	12	18	23	1
Weight of roots — grams	4	5	5	5	1	2	5	7	6	1
Protein in grain — per cent	10.7	10.8	11.6	12.8	5	11.6	10.6	10.5	10.2	5
Total protein — grams	1.25	1.53	1.88	2.21	1	0.60	0.89	1.26	1.64	1

¹Any two means underscored by the same line are not significantly different at the levels indicated



